Dark Matter Searches and Other Physics Signals in XENON1T, XENONnT and DARWIN

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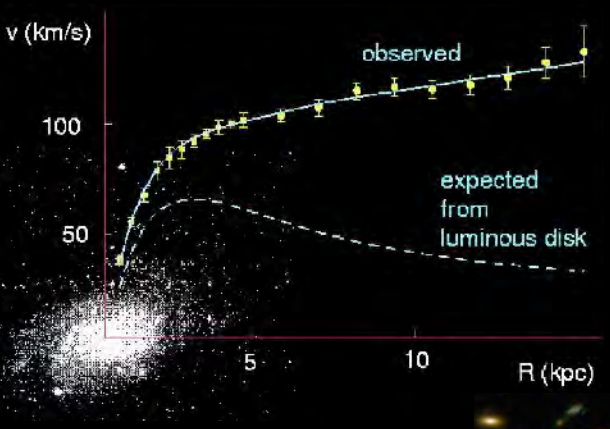
XENON
Dark Matter Project

Universiteit van Amsterdam

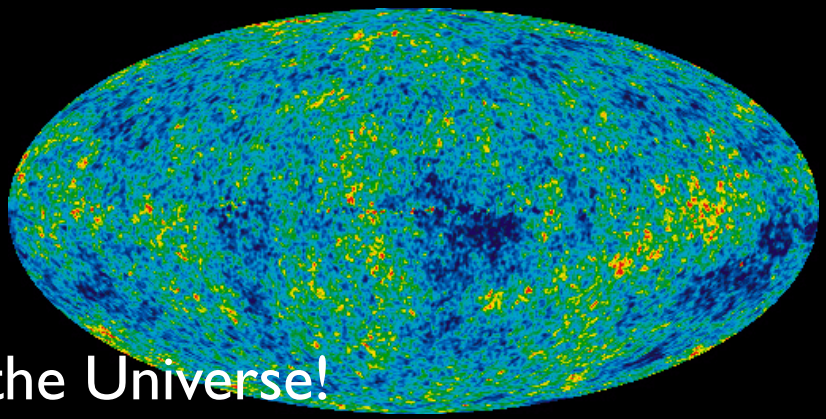
GRAPPA
GRavitation AstroParticle Physics Amsterdam

Nikhef

Much astrophysical evidence for Dark Matter



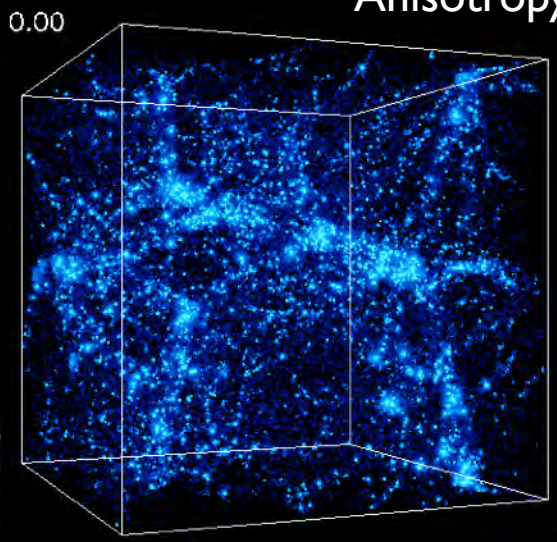
Rotational Curves



Anisotropy in CMB

On **all** distance scales in the Universe!

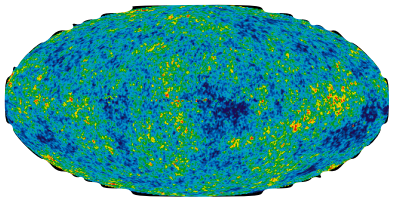
Weak Lensing

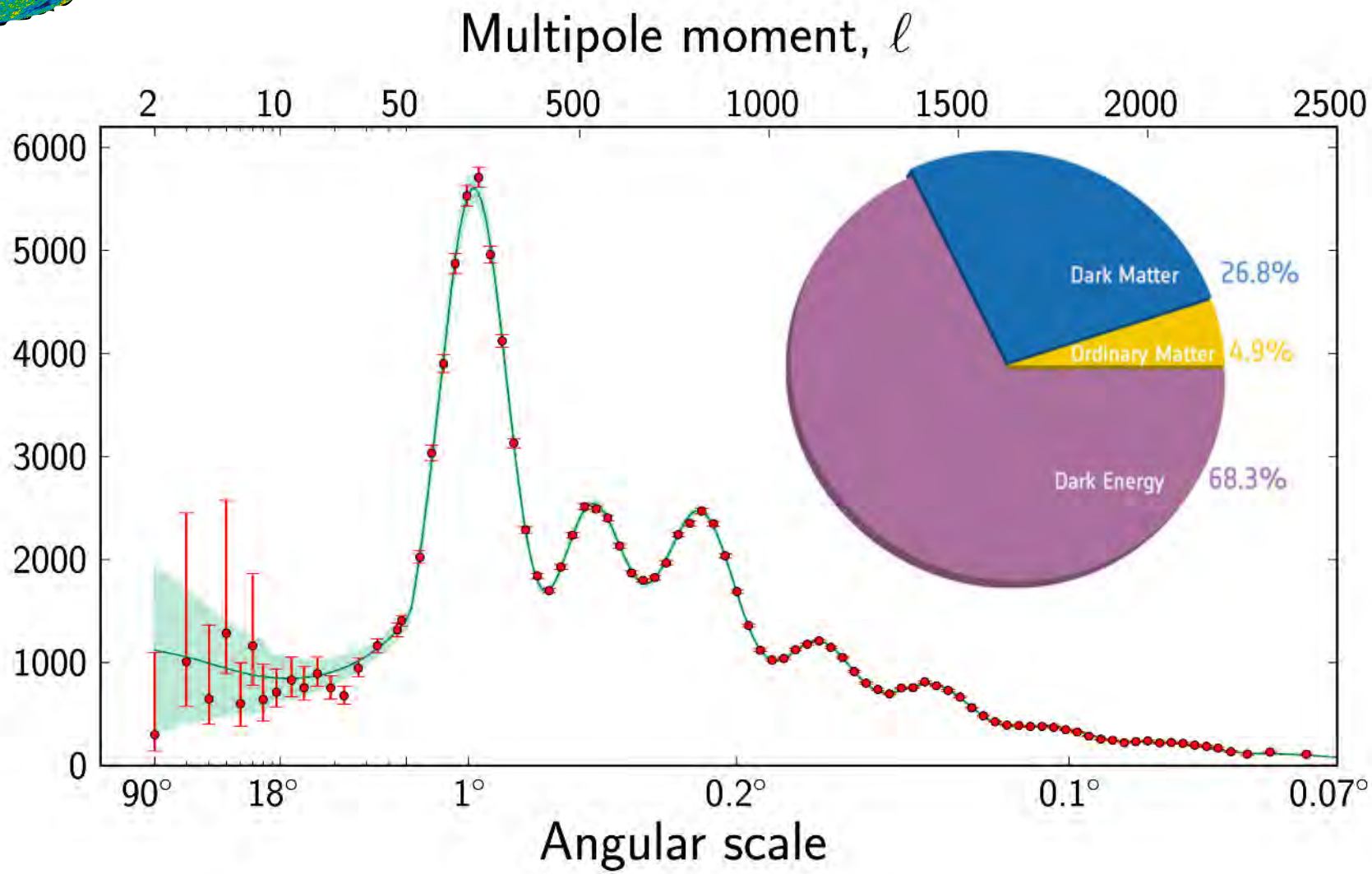


Large Scale Structure

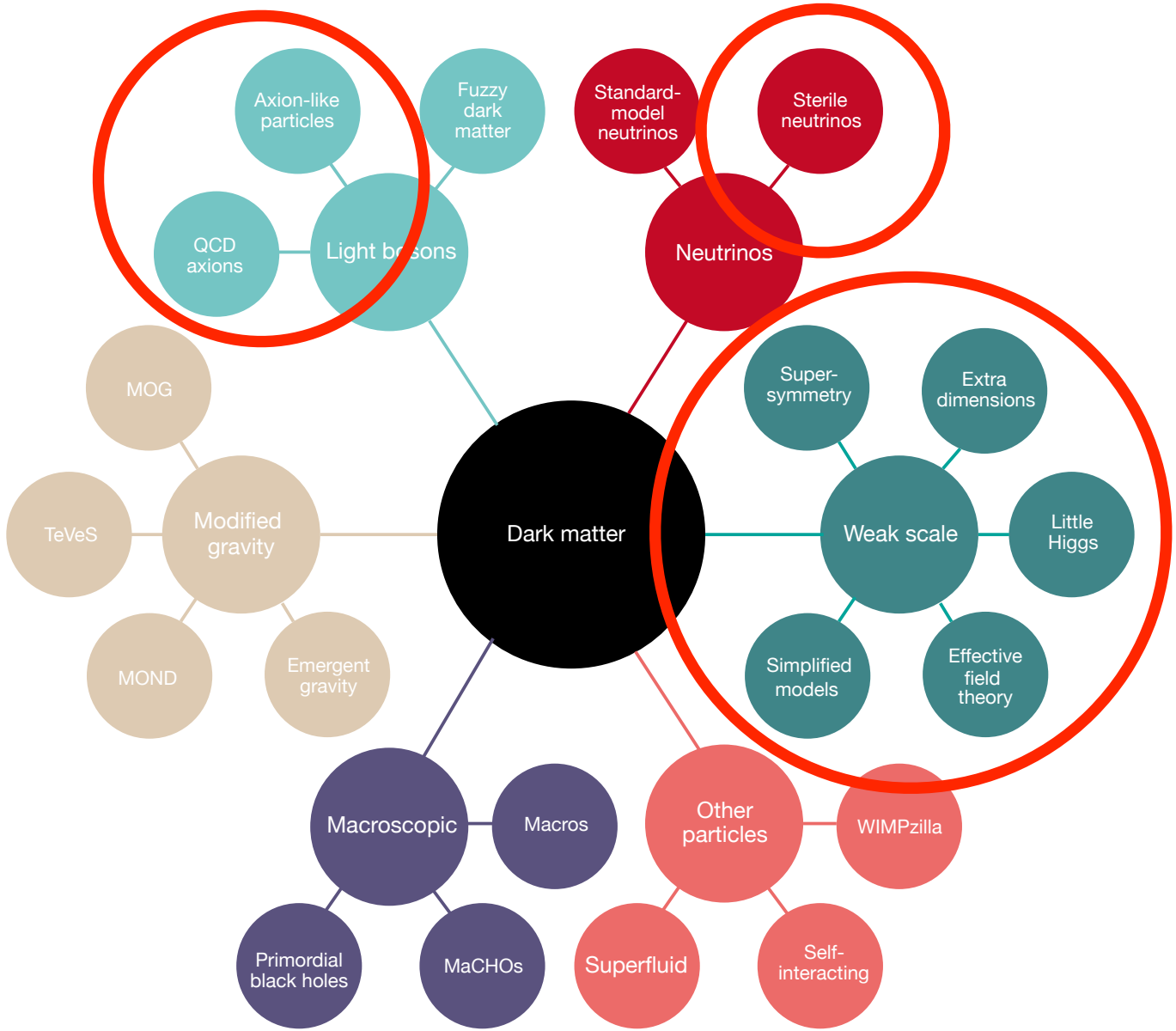
Galaxy Clusters

Cosmological Evidence for DM



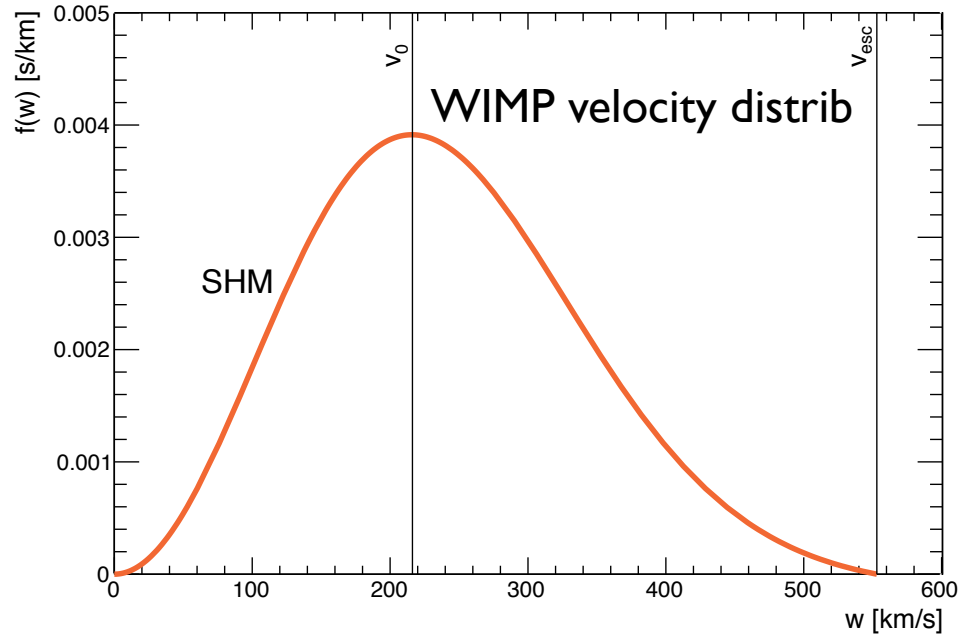


Dark Matter Candidates



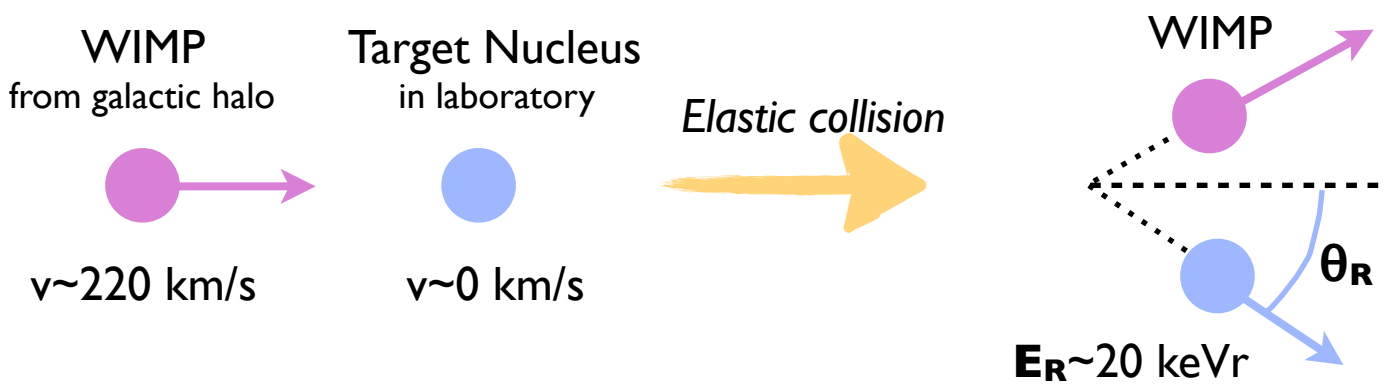
Bertone, Tait, Nature 562, 51

Detection of DM Particle Recoils



Assume WIMP is not only gravitationally interacting

M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).



$$E_R = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta)$$

$$v_{\min} = \sqrt{\frac{m_T E_{th}}{2\mu^2}}$$

What can be measured?

We measure:

$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \frac{d\sigma}{dE_R} v f(v, v_e(t))$$

Need input from Astrophysics

Effective interaction Lagrangian (low E limit, $v_{WIMP} \sim 10^{-3}c$):

$$\mathcal{L}_{\rm eff} = f_q \overline{\chi}\chi\overline{q}q + d_q \overline{\chi}\gamma^\mu\gamma^5\chi\overline{q}\gamma_\mu\gamma^5 q + \ldots$$

Scalar Axial

with scalar (SI) and axial-vector (SD) couplings:

$$\frac{d\sigma}{dE_R} = \frac{m_T}{2\mu^2 v^2}\left[\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R)\right]$$

WIMP-Nucleus Cross Section

Spin-independent cross section:

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

Better sensitivity with high A

Spin-dependent cross section:

Need nucleus with spin:

^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs (but no Ar!)

Nuclear model:

$$\langle S_{p,n}\rangle = \langle N|S_{p,n}|N\rangle$$

$$\sigma_{SD} = \frac{32\mu^2}{\pi}G_F^2\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Only axial vector describing state of nucleus as q → 0

WIMP couplings to protons & neutrons

Analysis is done attributing **all** the (lack of) rate to SI or SD

Energy Recoil Spectra

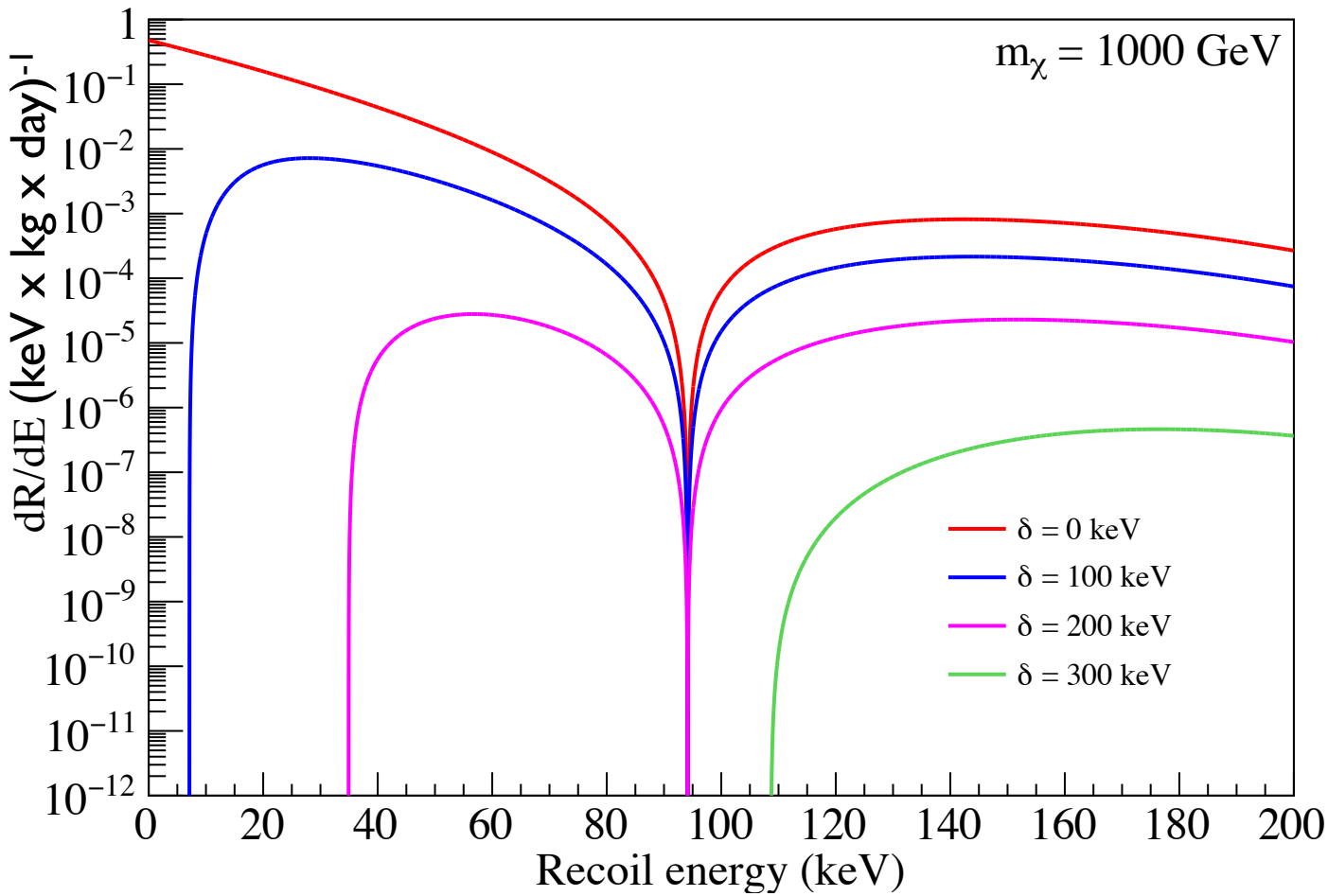
Inelastic Scattering: $\chi N \rightarrow \chi^* N$

Typically consider Elastic Scattering

δ is χ - χ^* mass splitting

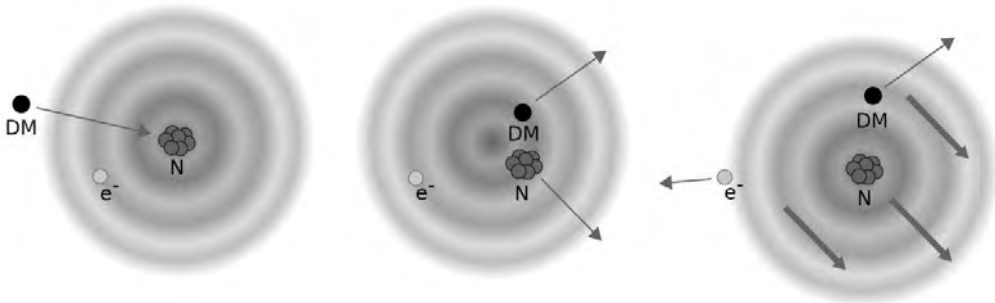
"Vanilla WIMP Model"

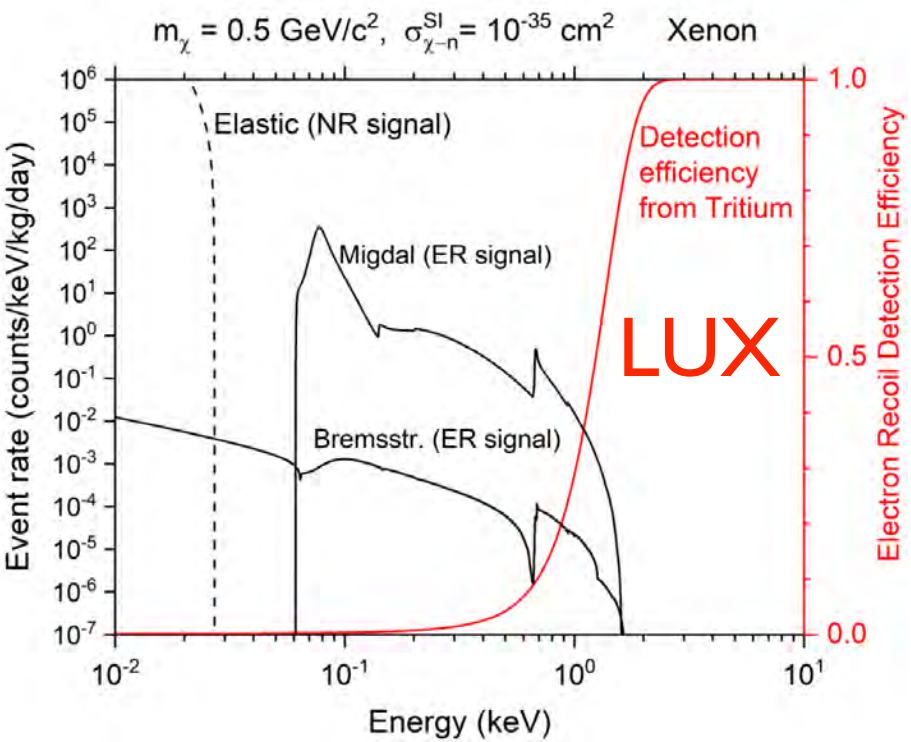
$$v_{min} = \sqrt{\frac{1}{2M_N E_{nr}}}\left(\frac{M_N E_{nr}}{\mu} + \delta\right)$$



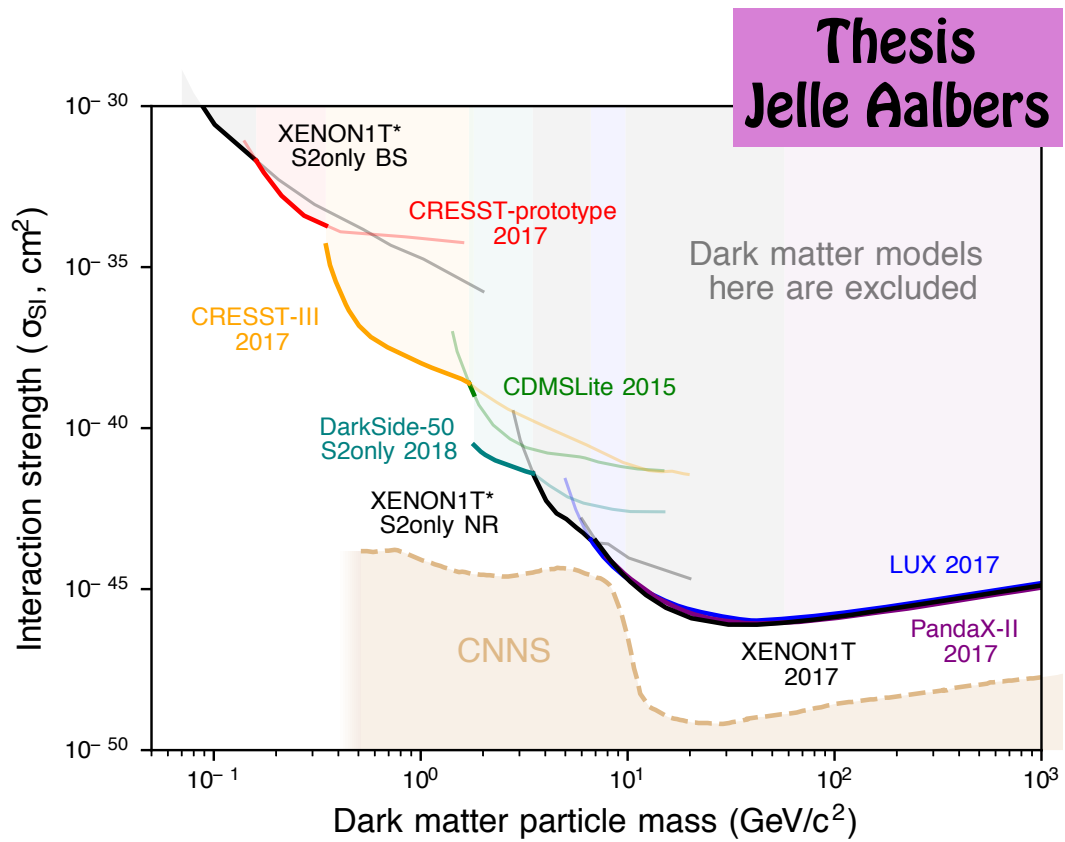
Searching for Sub-GeV WIMPs

"Migdal"-effect



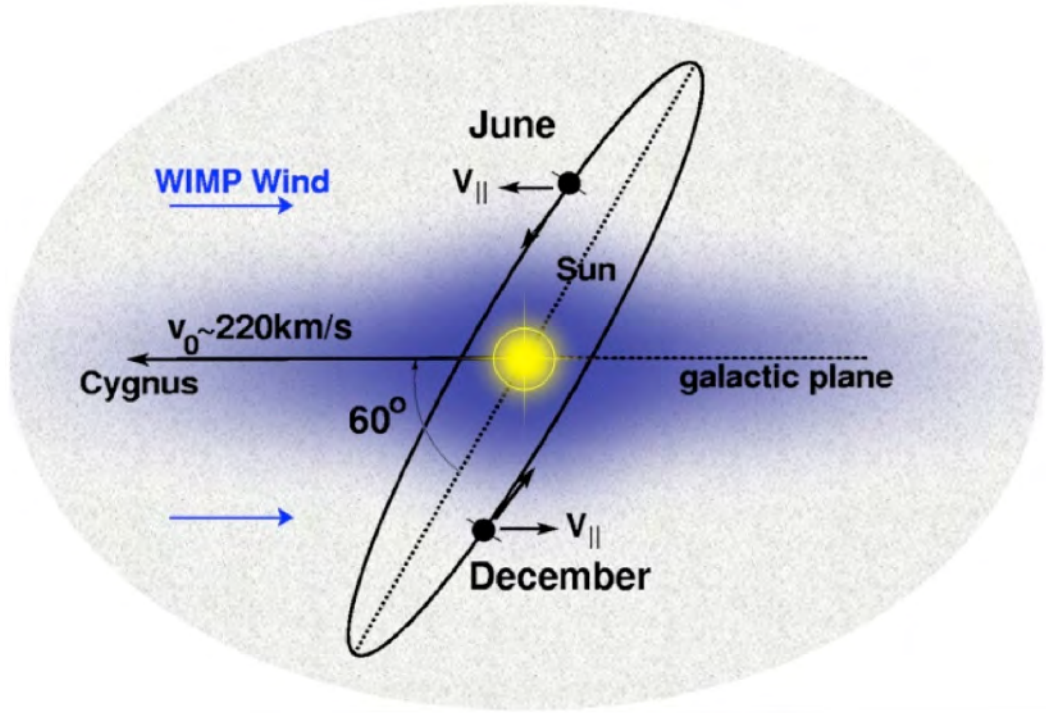


Other ways to get sub-GeV

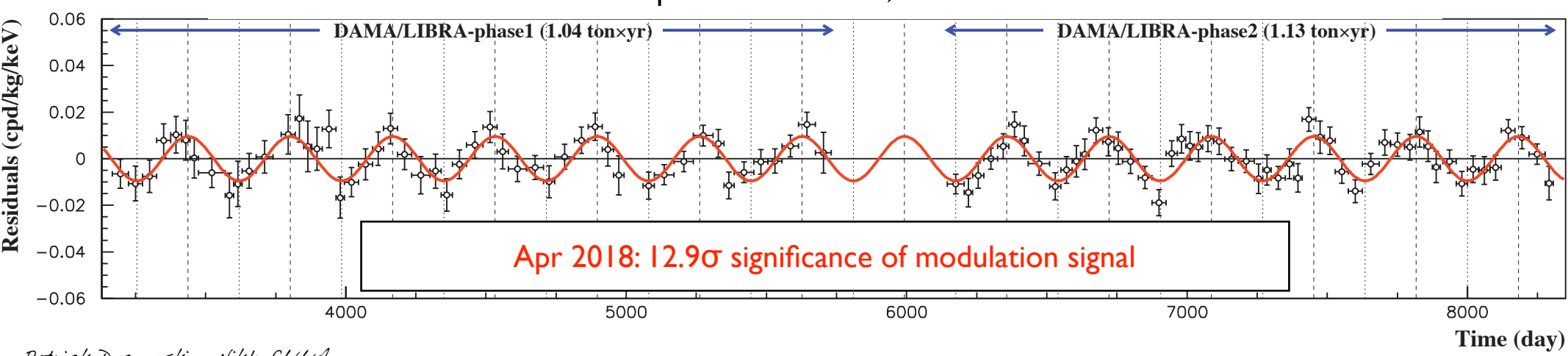


Drive to be sensitive to sub-GeV mass DM

Use annual modulation: DM claim



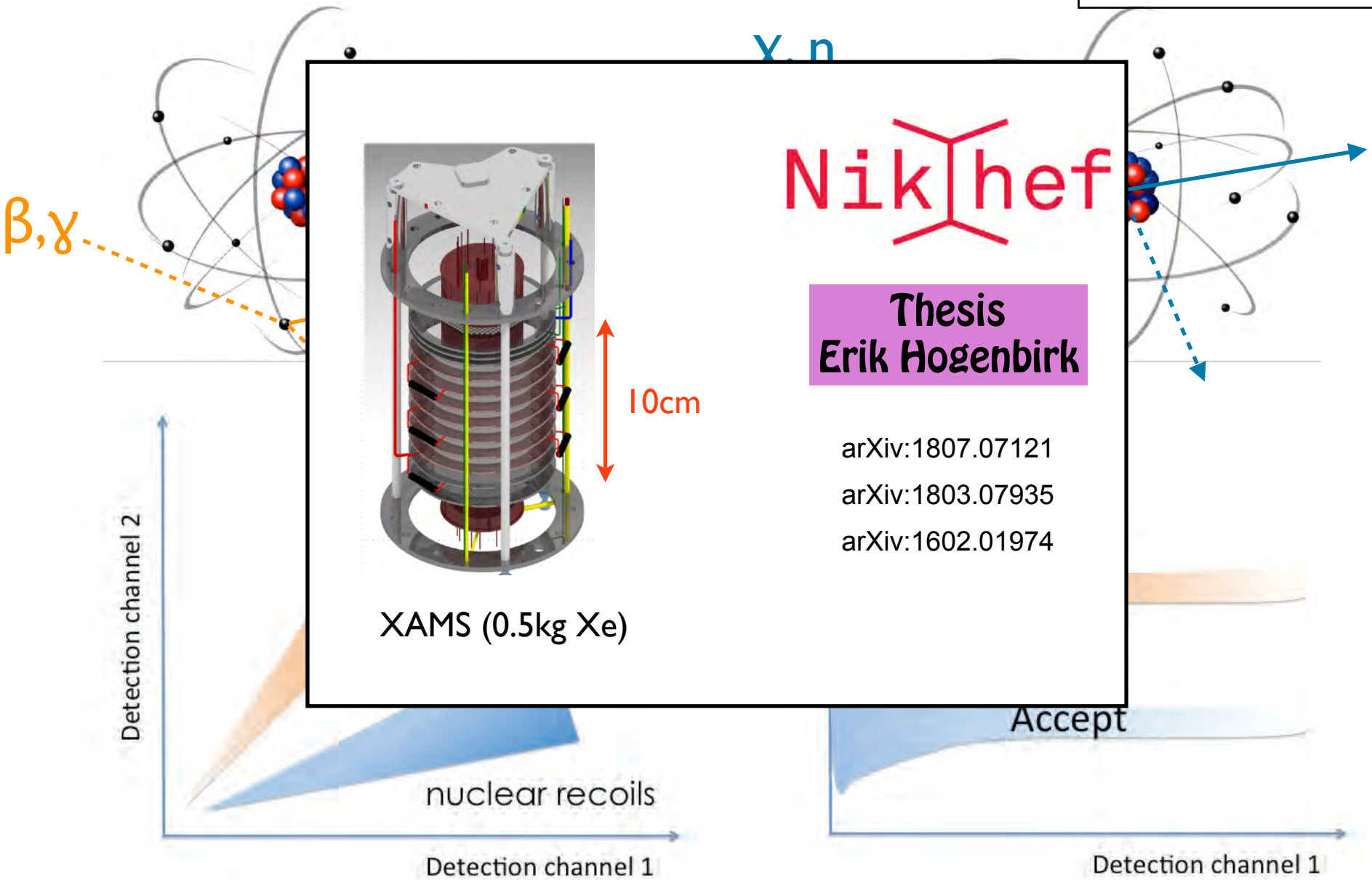
Modulation present in 2-6 keV, absent above 6 keV



Apr 2018: 12.9σ significance of modulation signal

Particle-dependent Response

CDMS, CRESST, DarkSide, LUX, XENON etc.



XAMS (0.5kg Xe)

Nikhef

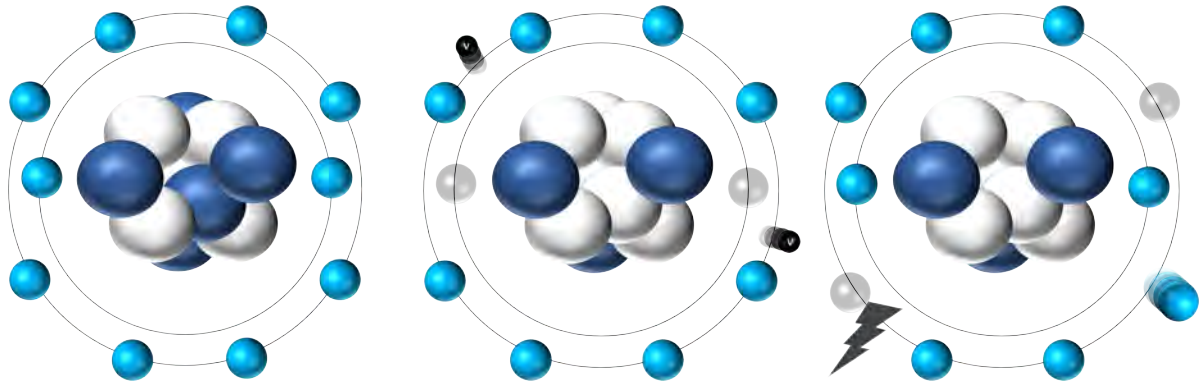
Thesis
Erik Hogenbirk

arXiv:1807.07121
arXiv:1803.07935
arXiv:1602.01974

Image E.Pantic

Patr

Double Electron Capture

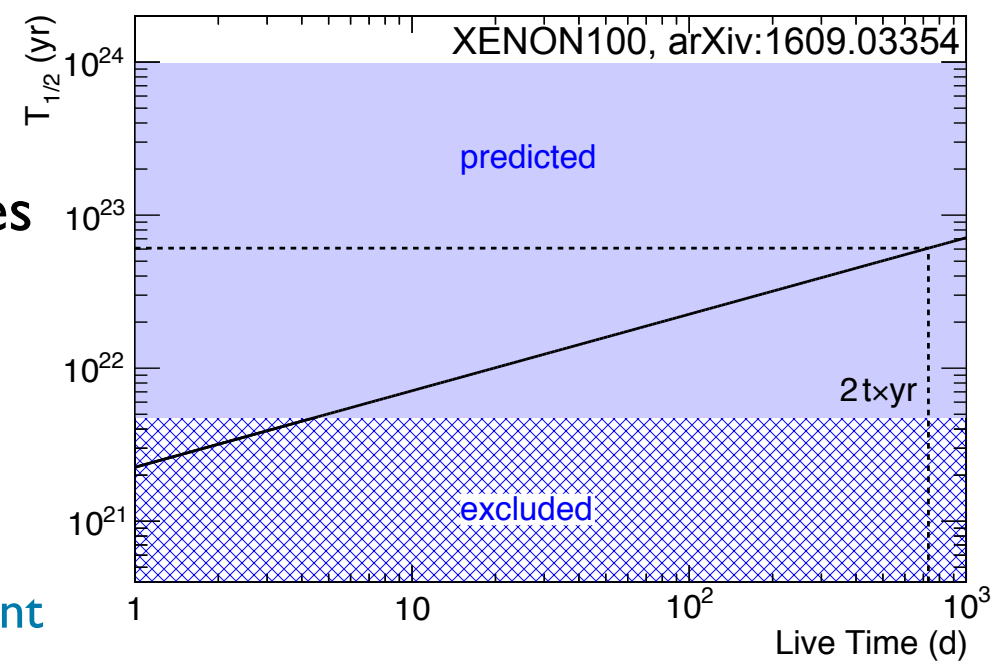


- Second order process like double β-decay, but longer lived - so far only measured in ^{130}Ba and ^{78}Kr
- ^{124}Xe is a candidate isotope
  - 0.095% Nat. abundance
  - Peak at 64.3 keV from K-shell captures

$$T_{1/2}^{2\nu 2EC} \propto G_{2\nu} |M_{2\nu}|^2$$

Phase Space Factor

Nuclear Matrix Element



Physics Channels

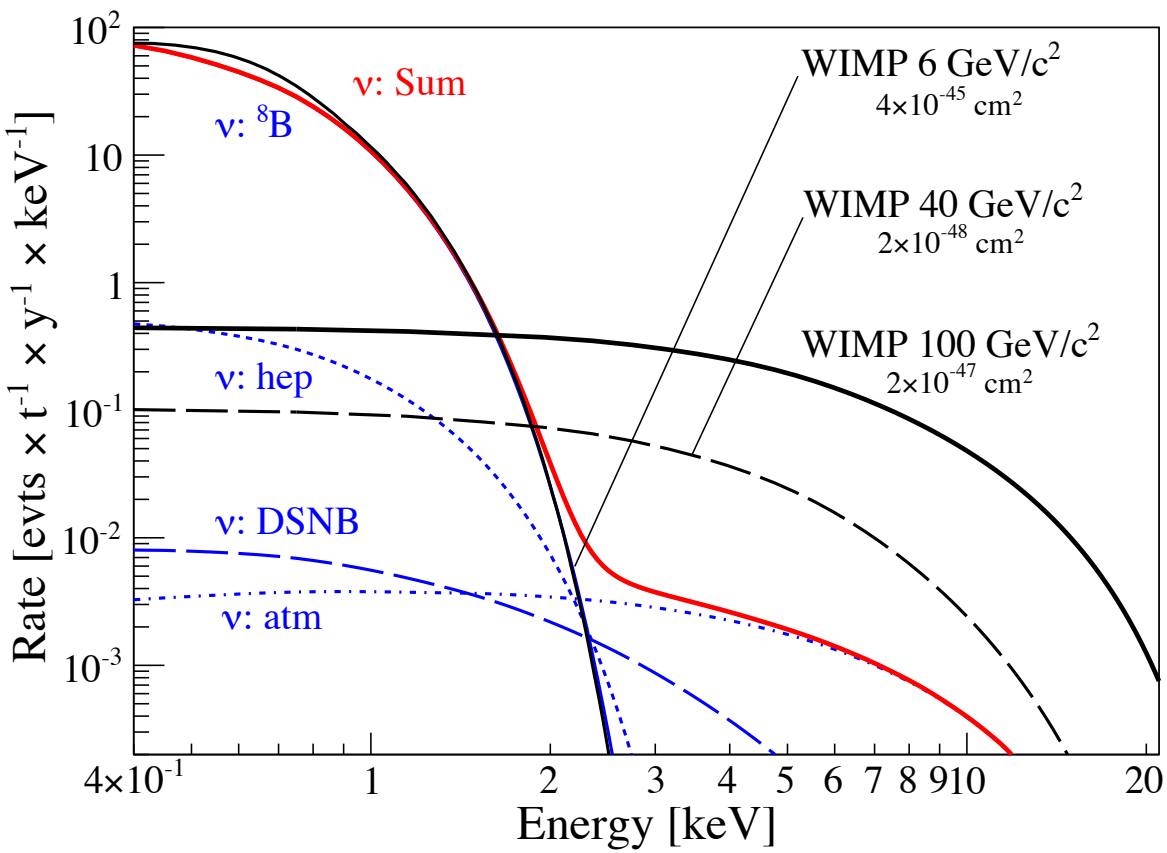
As detector size increases physics channels open up

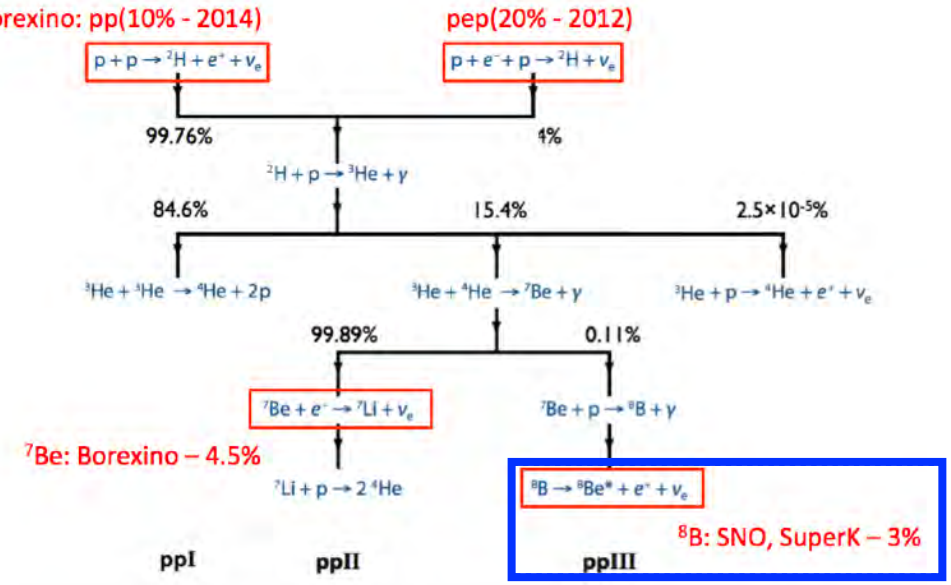
- **WIMP searches** NR
  - Spin-independent
  - Spin-dependent and inelastic interactions
- **Solar axions and galactic axion-like particles (ALPs)** ER
  - Alternative dark matter candidates
  - Coupling to electrons via axio-electric effect
- **Supernova neutrinos** NR
  - Sensitivity to all neutrino flavors (via CNNS)
  - Complementarity to large-scale neutrino detectors
- **Coherent neutrino-nucleus scattering (CNNS)** NR
  - Predicted by SM, *only very recently observed!*
- **Low-energy solar neutrinos: pp, ^{7}Be** ER
  - Test/improve solar model, test neutrino models
- **Neutrinoless double beta decay** ER
  - Lepton number violating process, effective Majorana mass
  - No enrichment in ^{136}Xe required

Coherent Neutrino-Nucleus Scattering

JCAP 01, 044 (2014)

- $\nu + N_{Xe} \rightarrow \nu + N_{Xe}$
- Predicted by SM, recently observed
- CNNS is background for WIMPs,
- Steeply falling spectrum

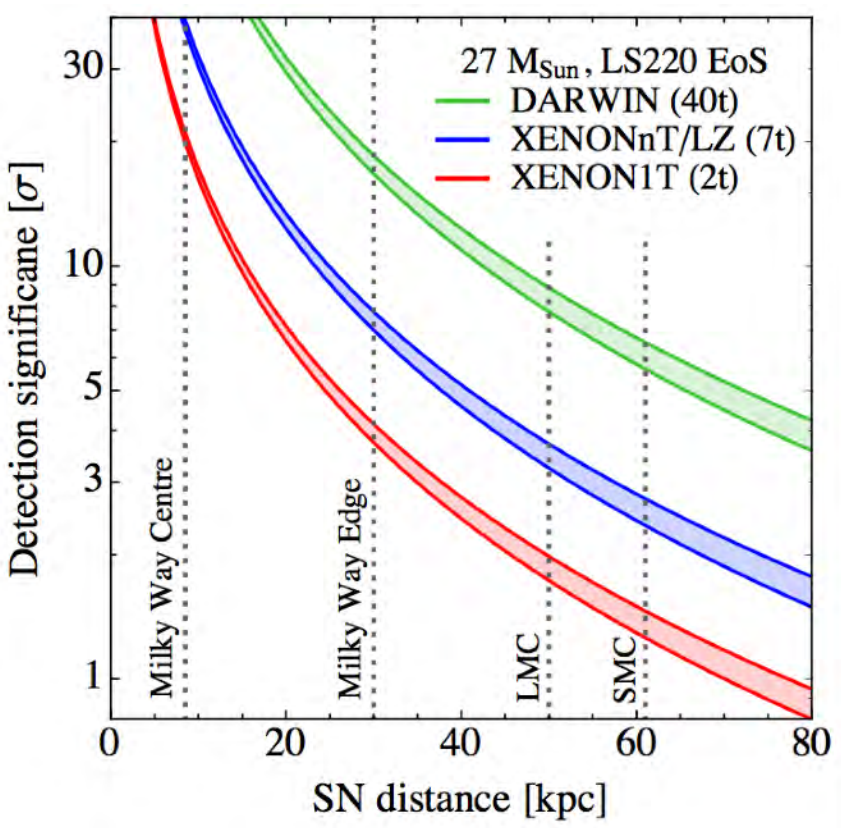


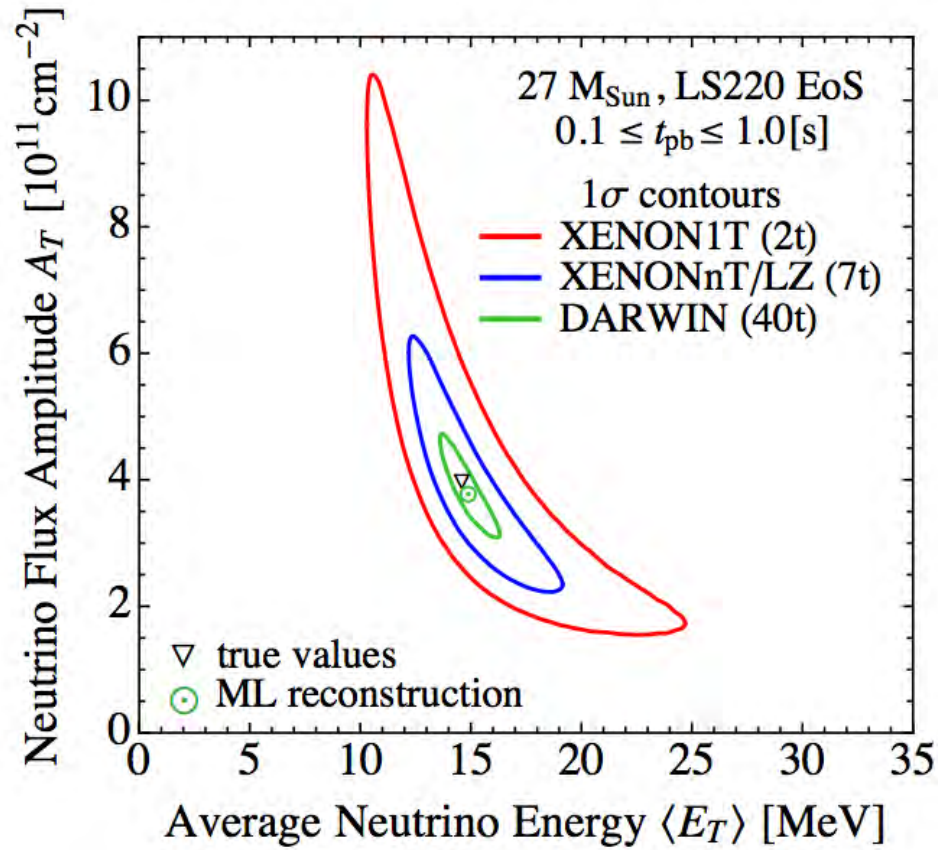


Supernova Neutrinos

R. Lang et al., arXiv:1606.09243

- Low threshold (due to S2-only)
- Negligible background due to short burst (~sec)
- >5σ sensitivity to a supernova burst in Milky Way
- Detection of all 6 neutrino species via neutral current reactions



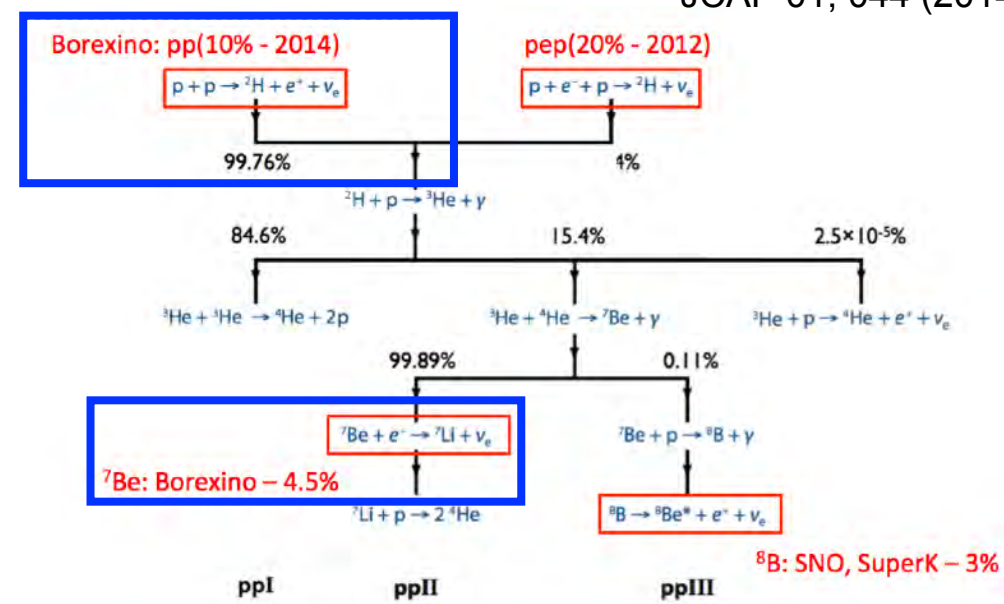


- **Hundreds** of events for a 27M$_\odot$ SN progenitor at 10 kpc
- Flavor-insensitive neutrino energy measurement
  → constrain total explosion energy and reconstruct the SN light curve

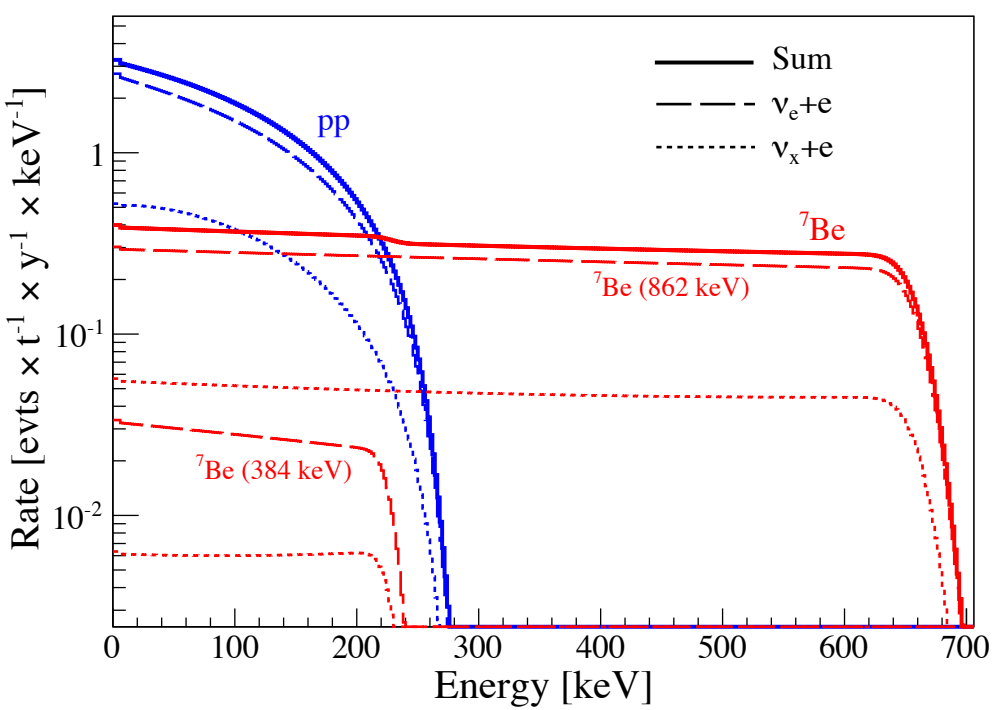
Solar Neutrinos

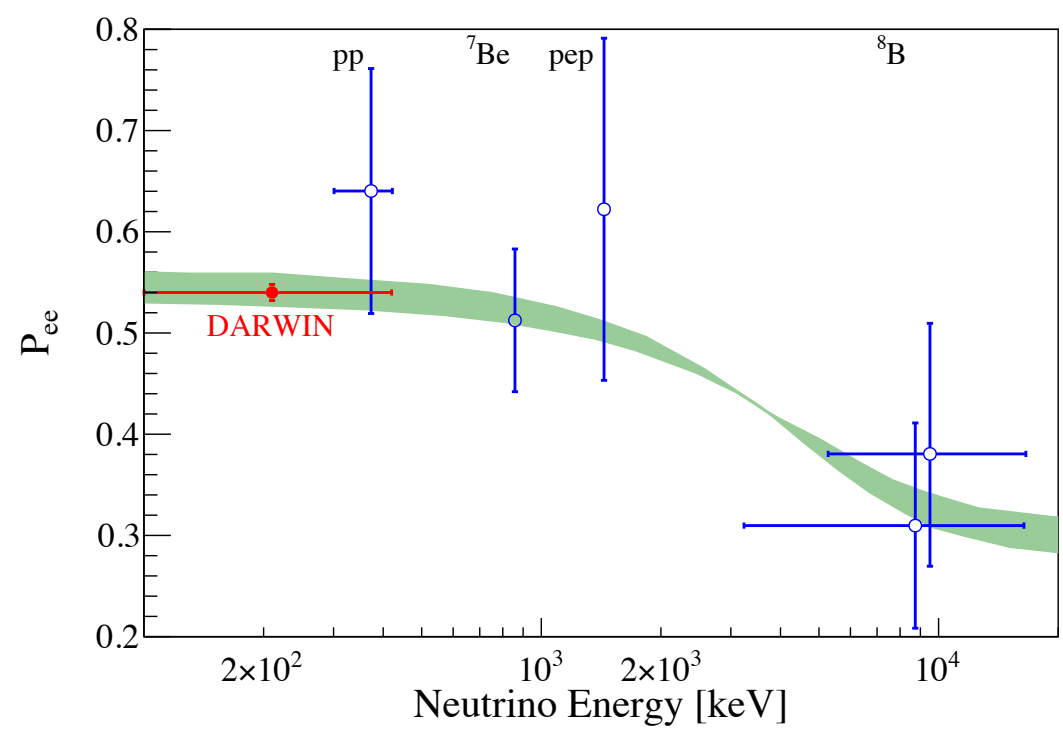
- Neutrino-electron elastic scattering
- Real-time measurement of neutrino flux
  → 7.2 events/day from pp (40 ton LXe detector)
  → 0.9 events/day from ^{7}Be
- 2% (1%) *statistical* precision after 1 year (5 years)
  → constrain solar models
- Neutrino survival probability measurement
  → deviation from prediction indicates new physics
- Atomic binding effects have to be taken into account!

JCAP 01, 044 (2014)



Chen et al, arXiv:1610.04177

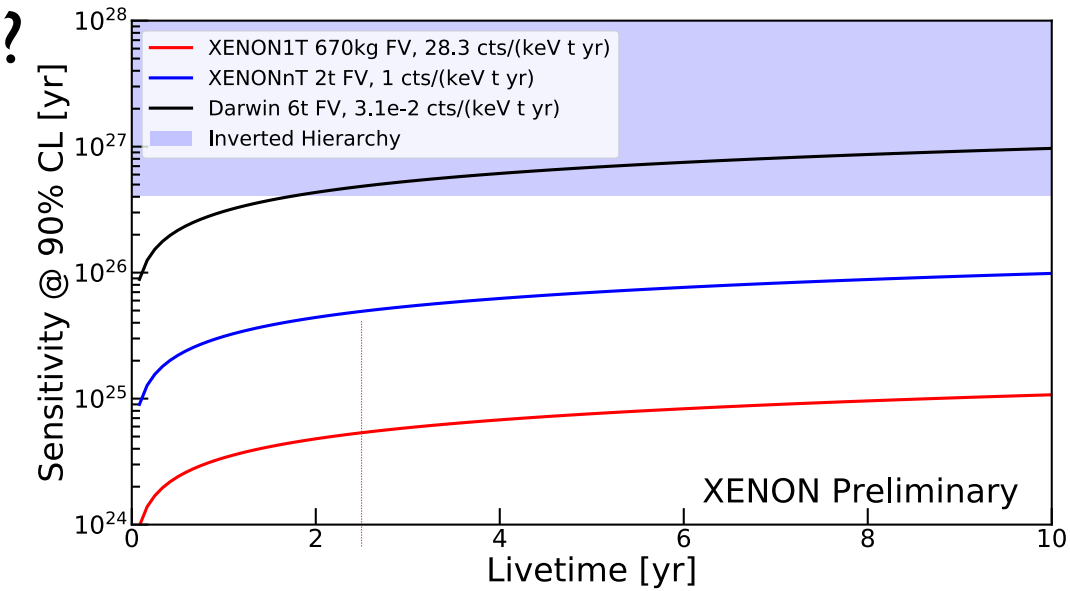




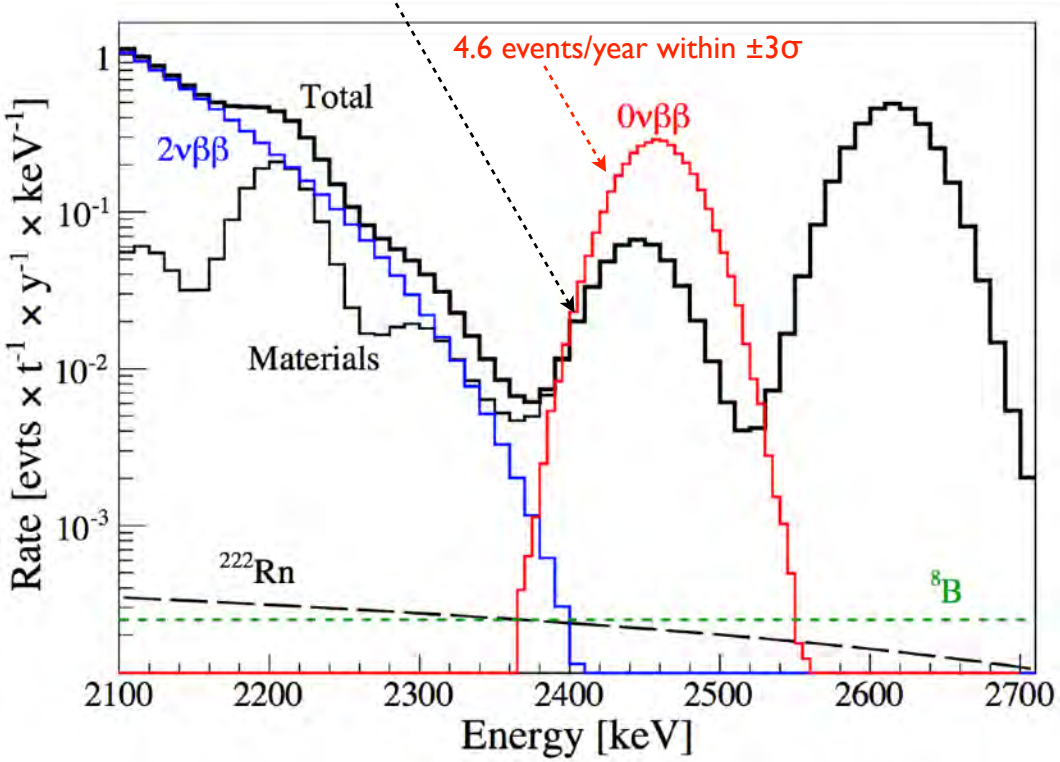
Neutrinoless Double Beta Decay

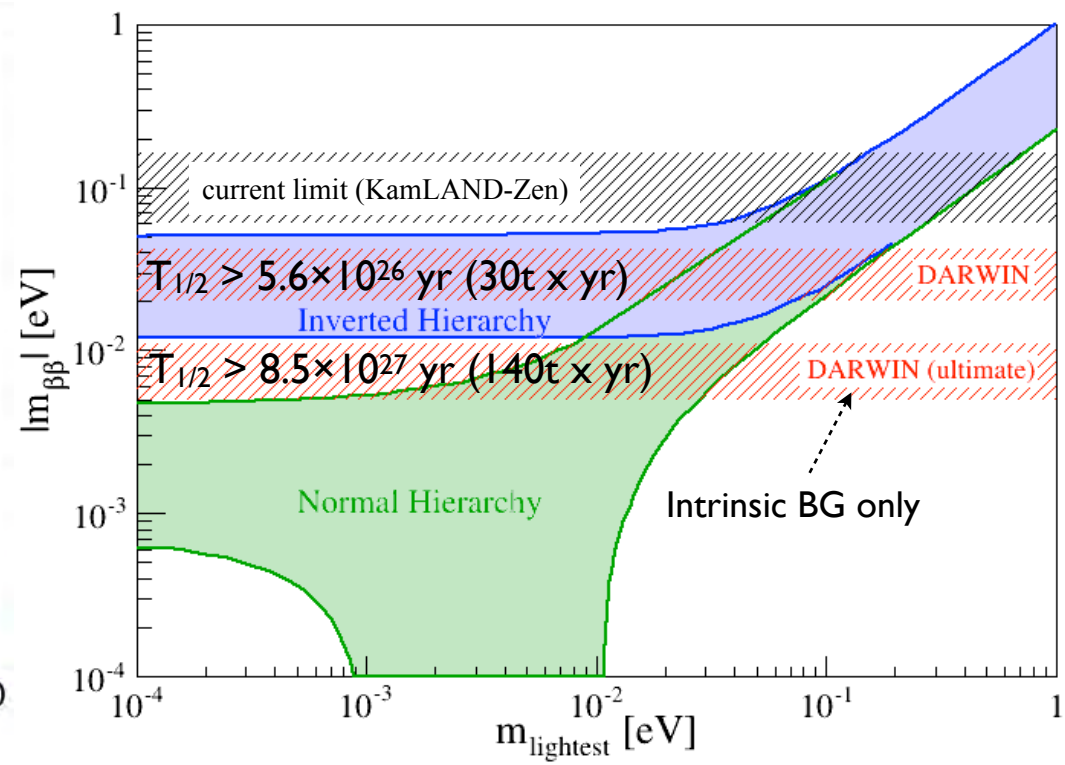
Is the neutrino a Majorana particle?

- ^{136}Xe abundance in natural xenon 8.9%
  - 40t of Xe has 3.6t of ^{136}Xe
- Q-value (2458.7±0.6) keV
- Energy resolution (σ/μ) at $Q_{\beta\beta}$ 1%



^{214}Bi → ^{214}Po + e⁻ + γ (2448 keV)





JCAP 01, 044 (2014)

Xe

XENON

Dark Matter Project

25 institutions,
150 people

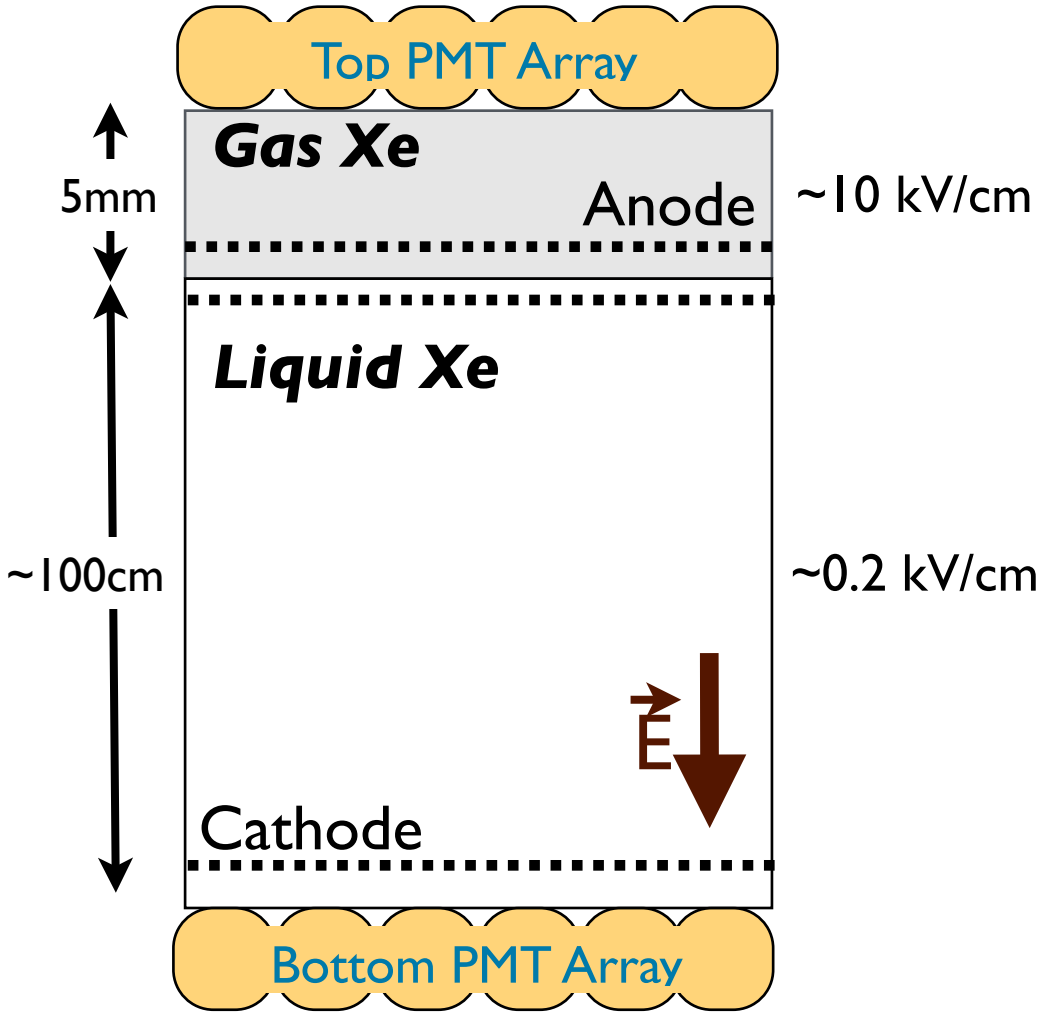
Completed / Operating / Planning:

XENON10, XENON100, XENON1T, XENONnT

Gran Sasso National Park near L'Aquila, Italy

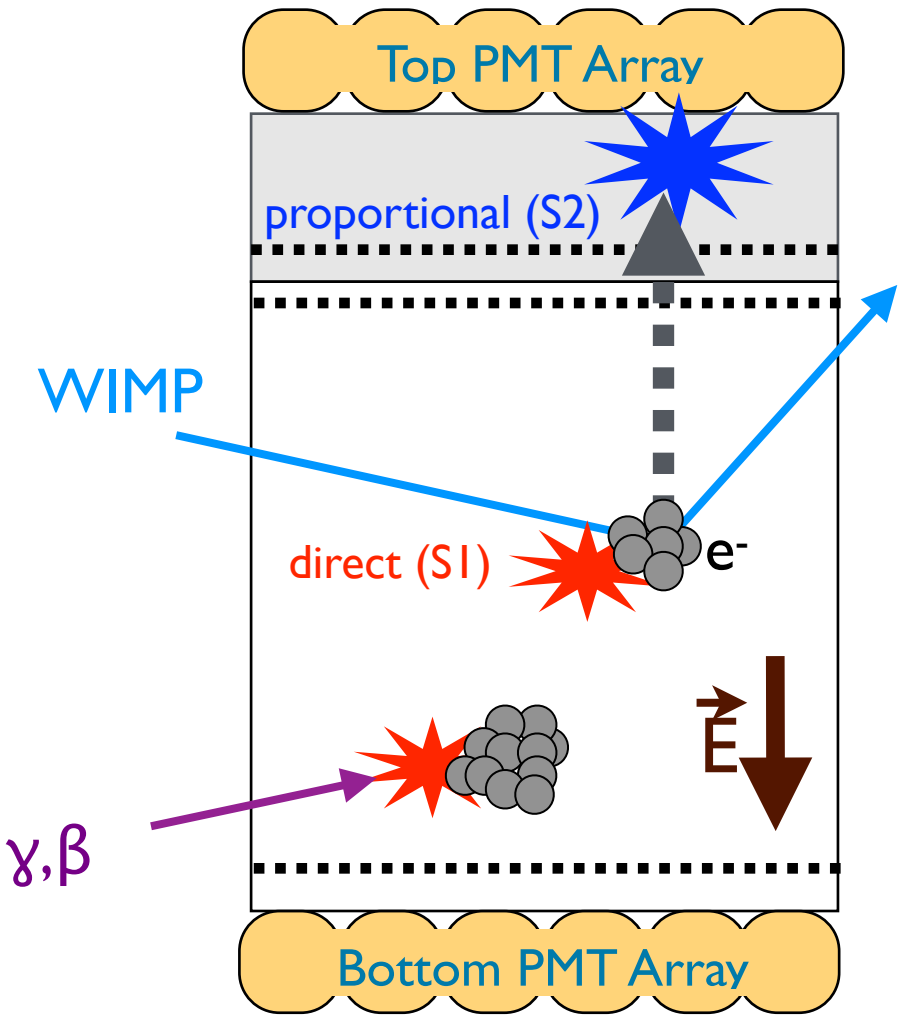

XENON1T Dark Matter Experiment

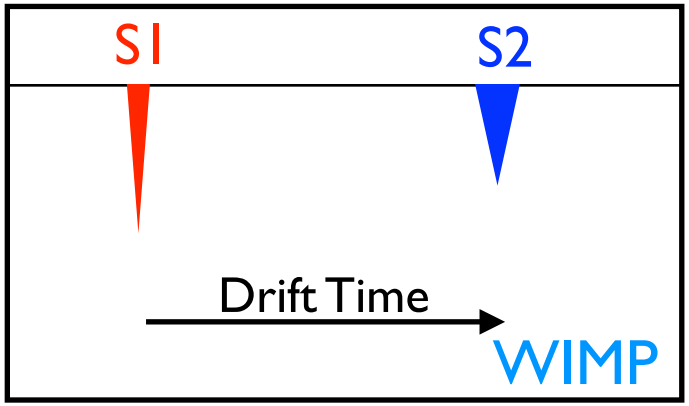
Dual-Phase Xe TPC



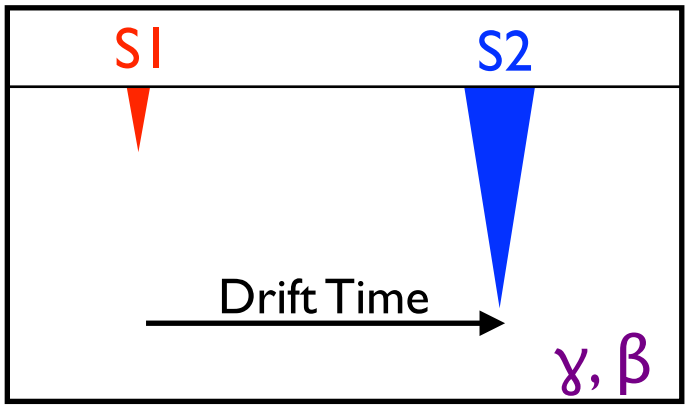
XENON1T: 3.2 tons of liquid xenon

Dual-Phase Xe TPC



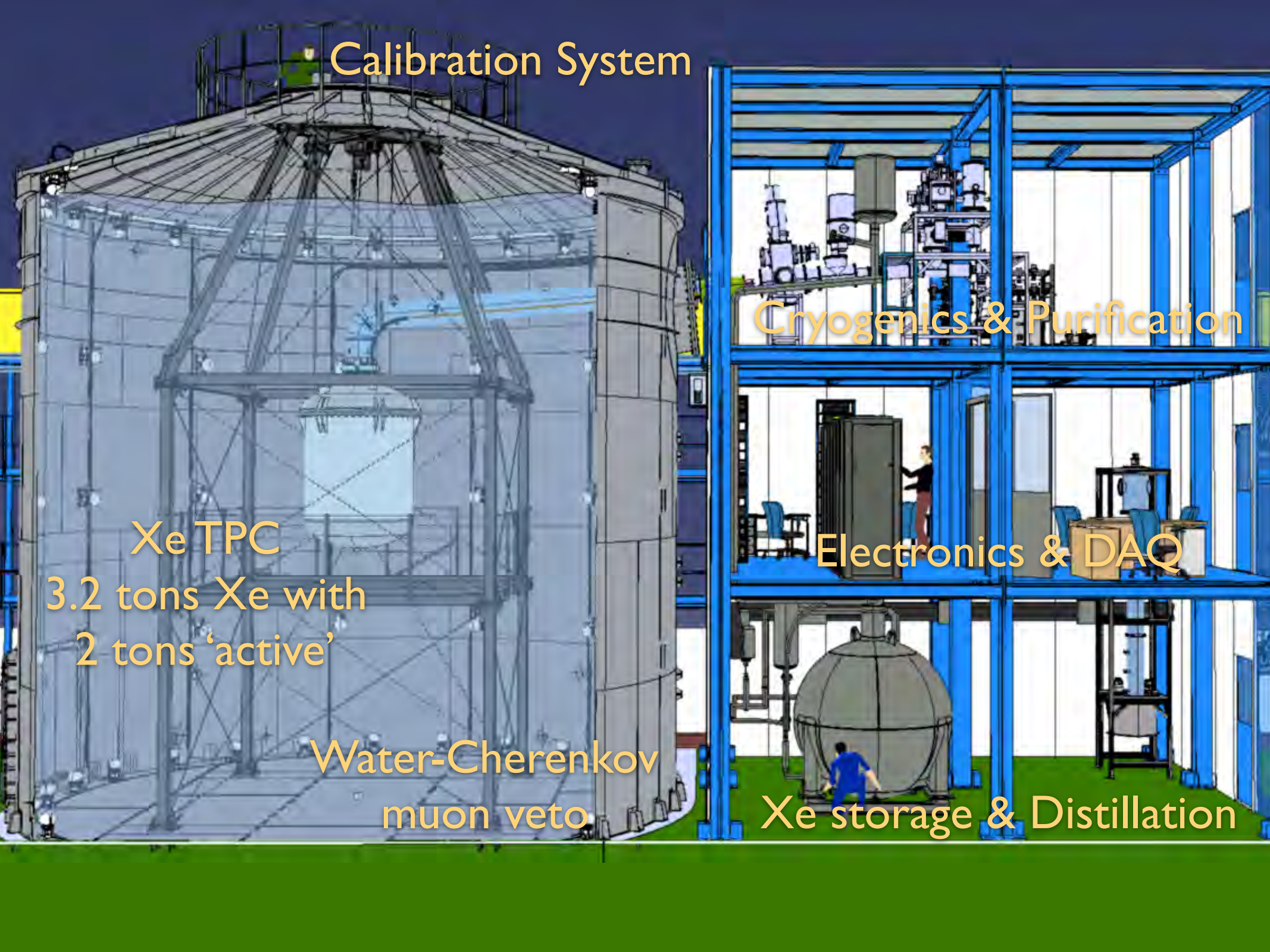


Signal:
Nuclear recoil



Background:
Electron recoil

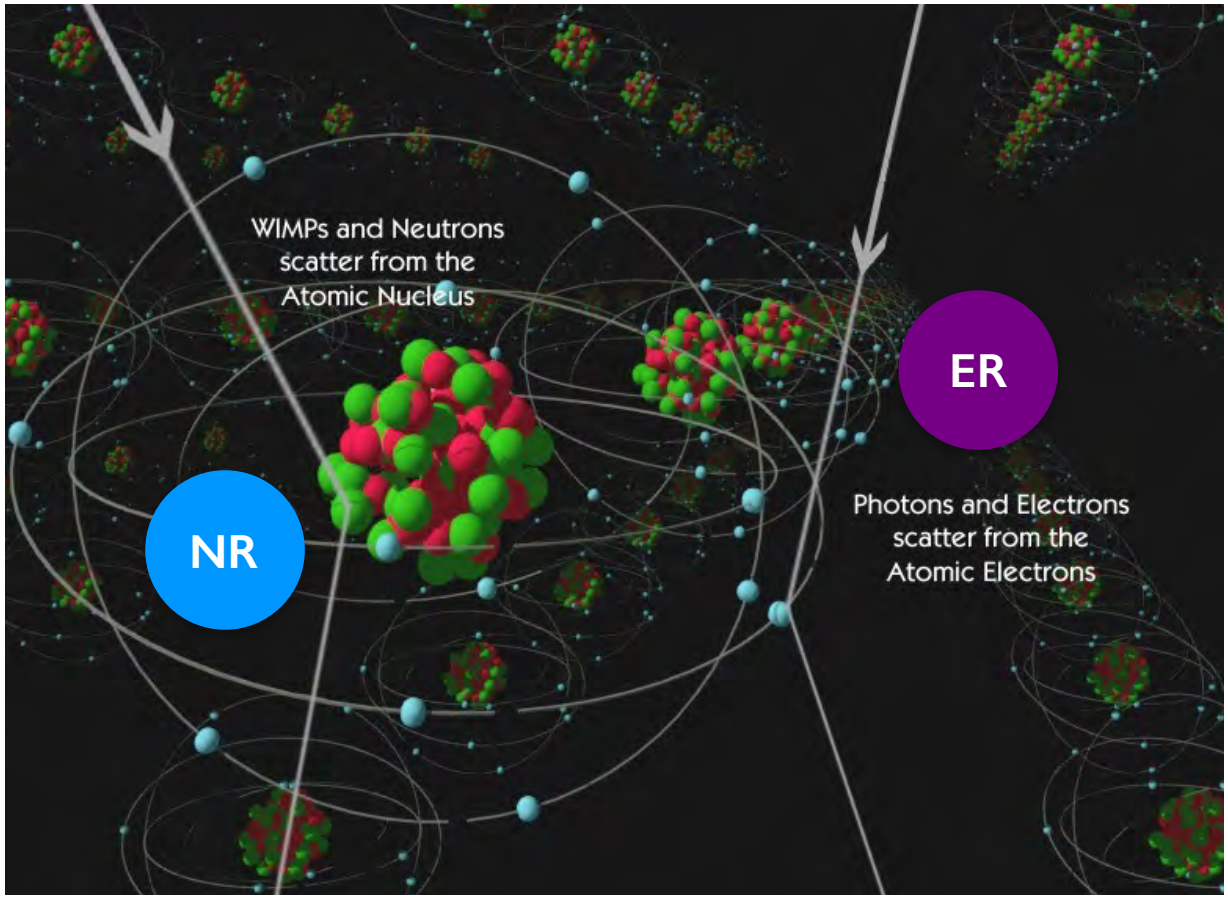
$$\frac{S2}{S1}_{\gamma,\beta} > \frac{S2}{S1}_{\mathrm{WIMP}}$$


Calibration System
Cryogenics & Purification
Xe TPC
3.2 tons Xe with
2 tons 'active'
Electronics & DAQ
Water-Cherenkov
muon veto
Xe storage & Distillation


Xe
XENON
Matter Project
XENON1
enlightening the

TPC assembly during Fall 2015

Main Backgrounds



Electronic recoils (ER):

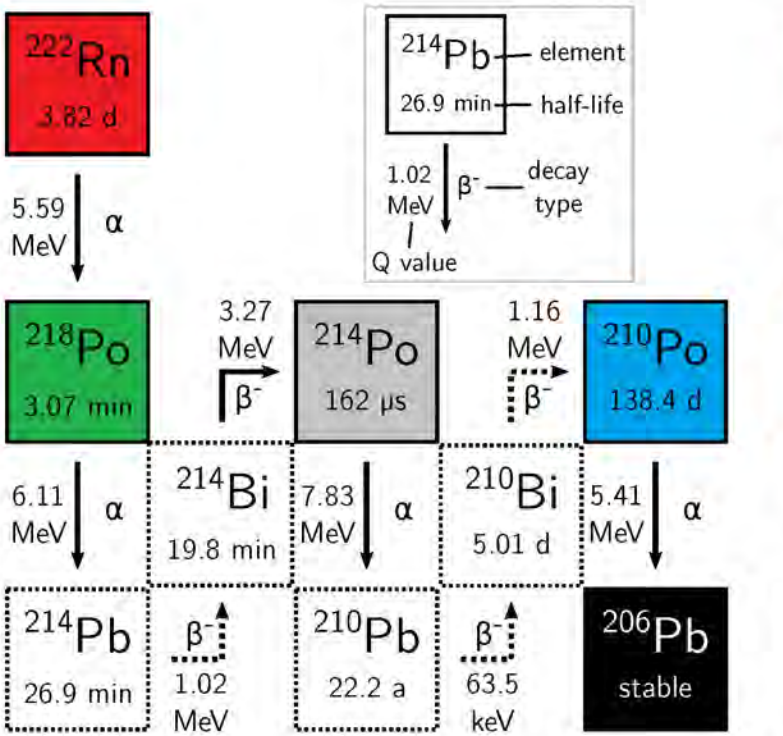
- **Materials**: Low energy Compton scatters from radioactive contamination in detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs
- **Solar neutrino** scattering off electrons
- **Intrinsic** contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe

Nuclear Recoils (NR):

- **Radiogenic neutrons**: spontaneous fission and (α, n) reaction from the U and Th chains in detector components
- **Muon-induced neutrons**
- **Coherent scattering of neutrinos** (mostly solar) off Xe nuclei

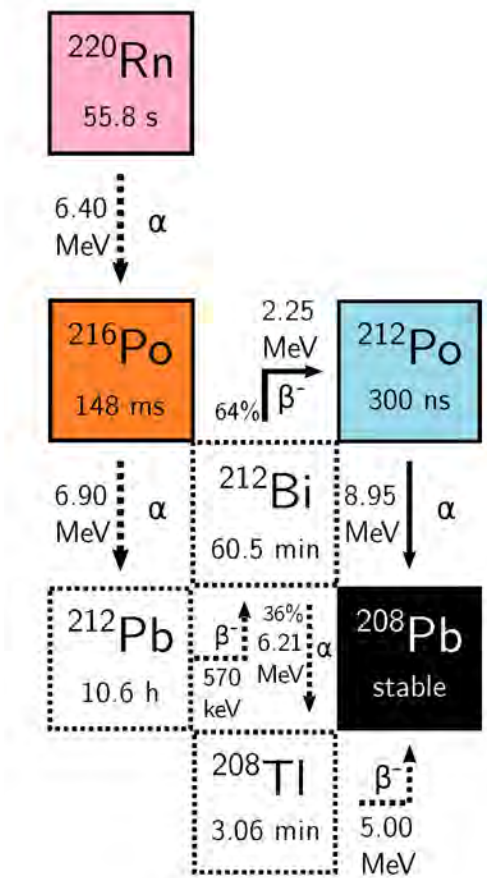
Radon decay chains

"Bad" Radon



Background

"Good" Radon

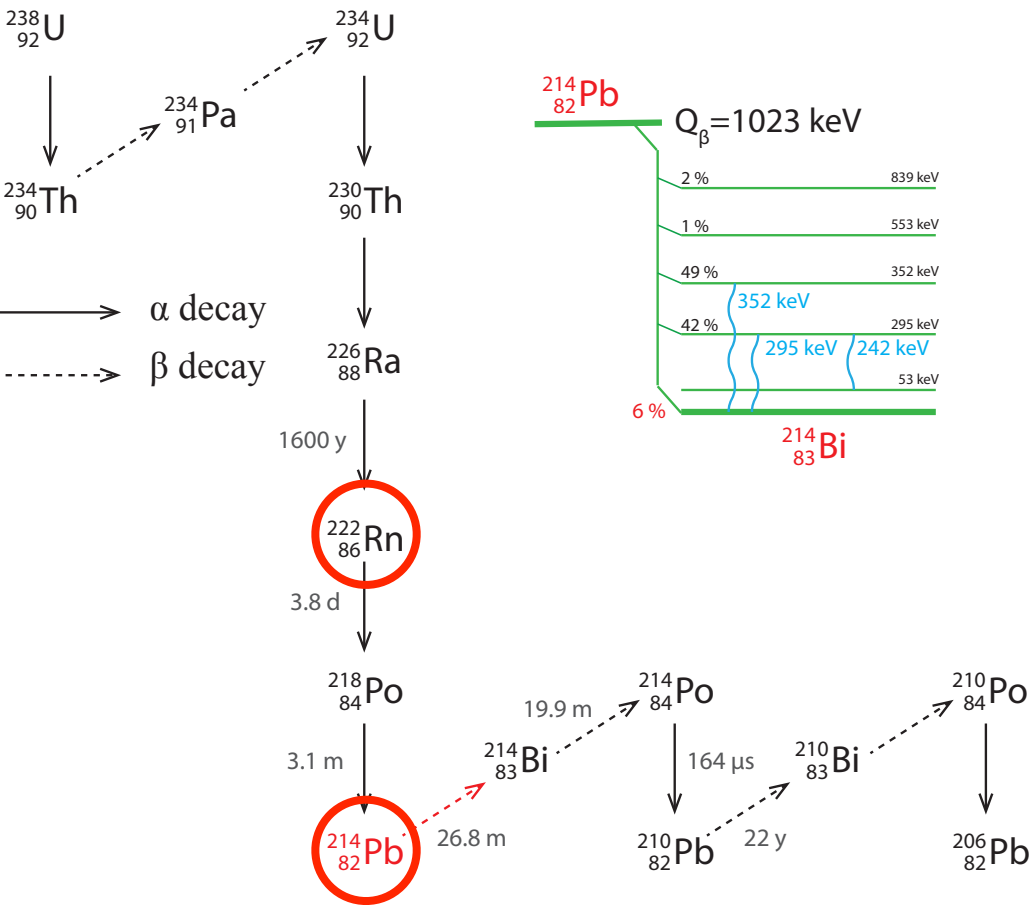


Calibration

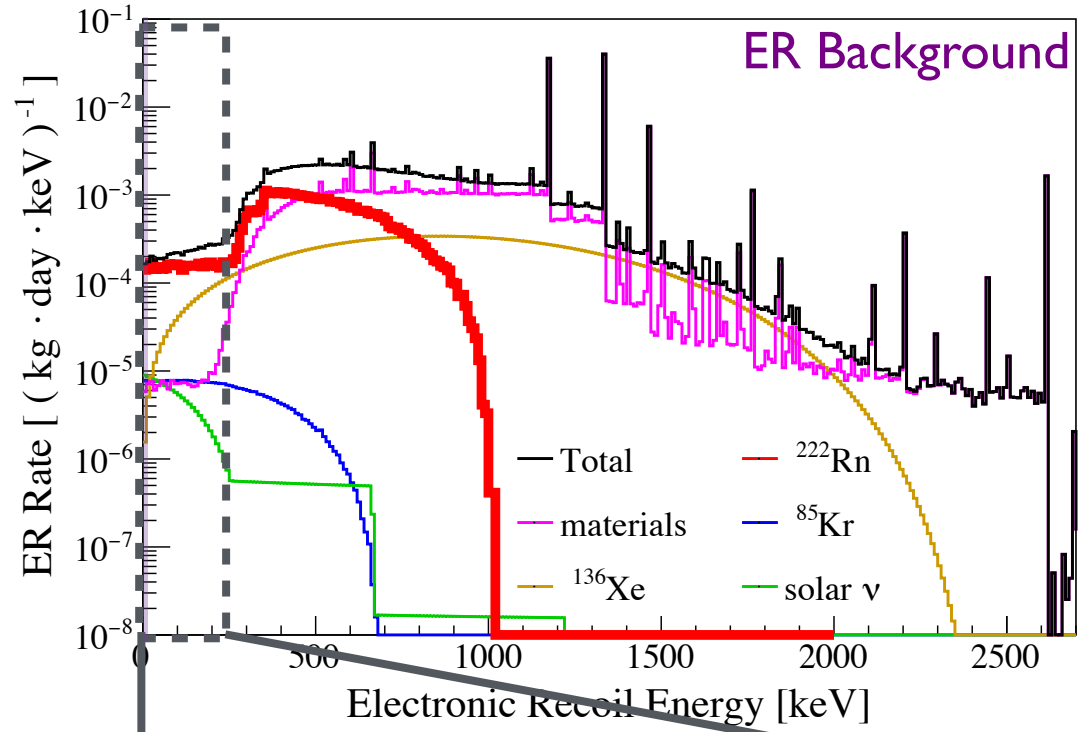
Thesis
Sander Breur

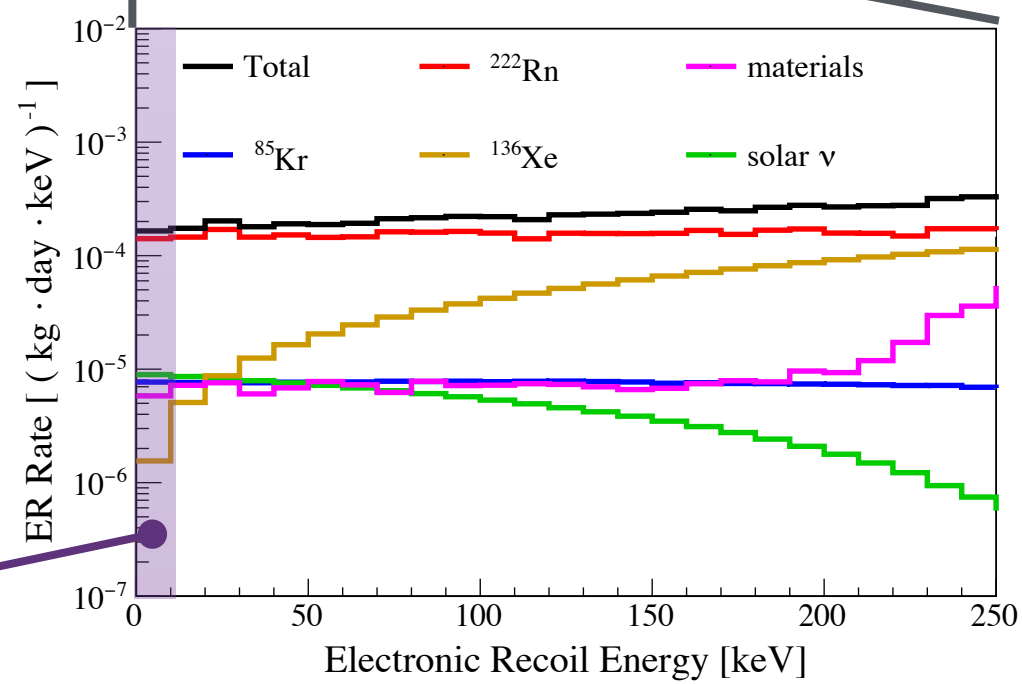
^{222}Rn background dominating

"Bad" Radon



Reached design goal of
10 μBq/kg ^{222}Rn concentration

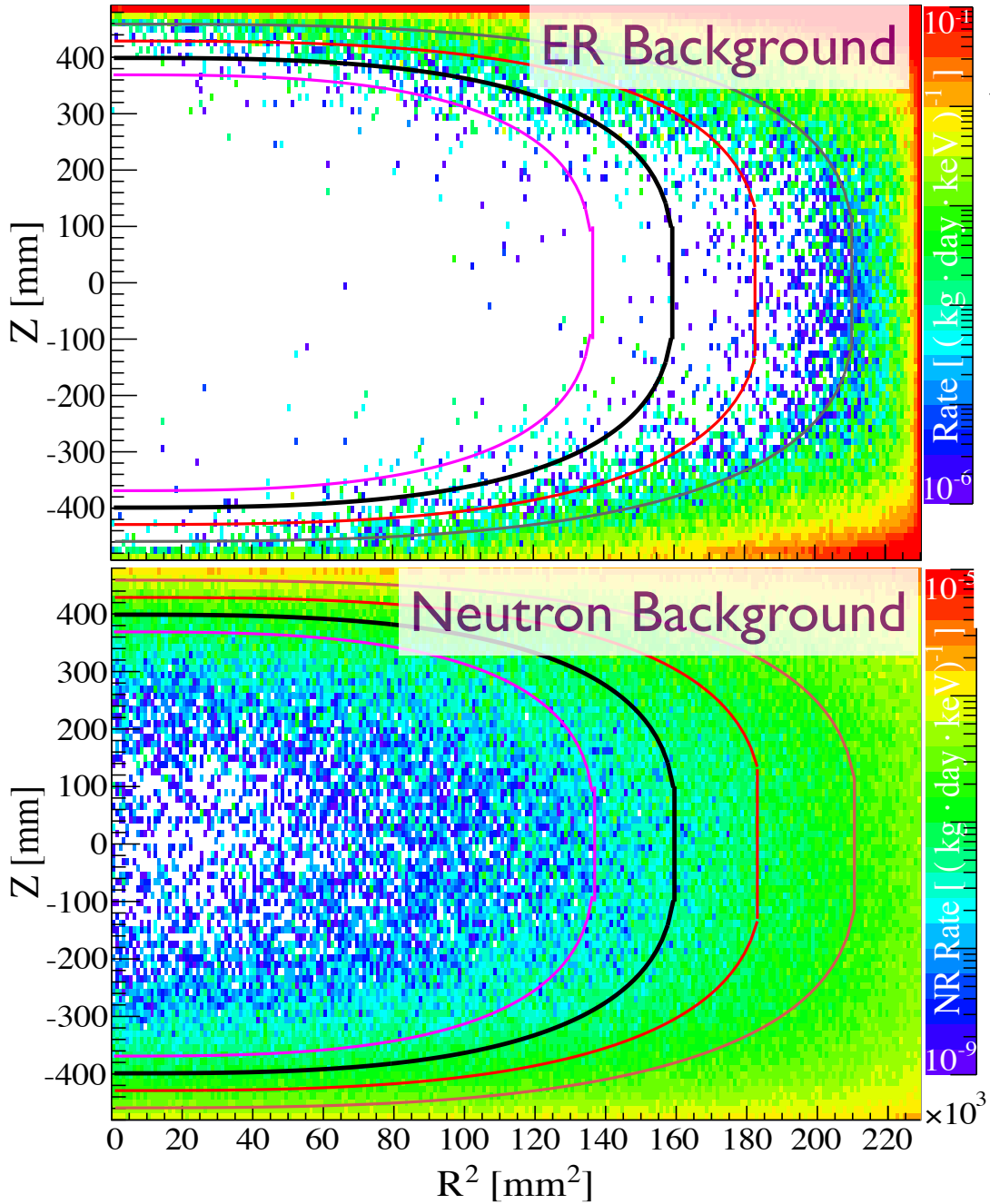


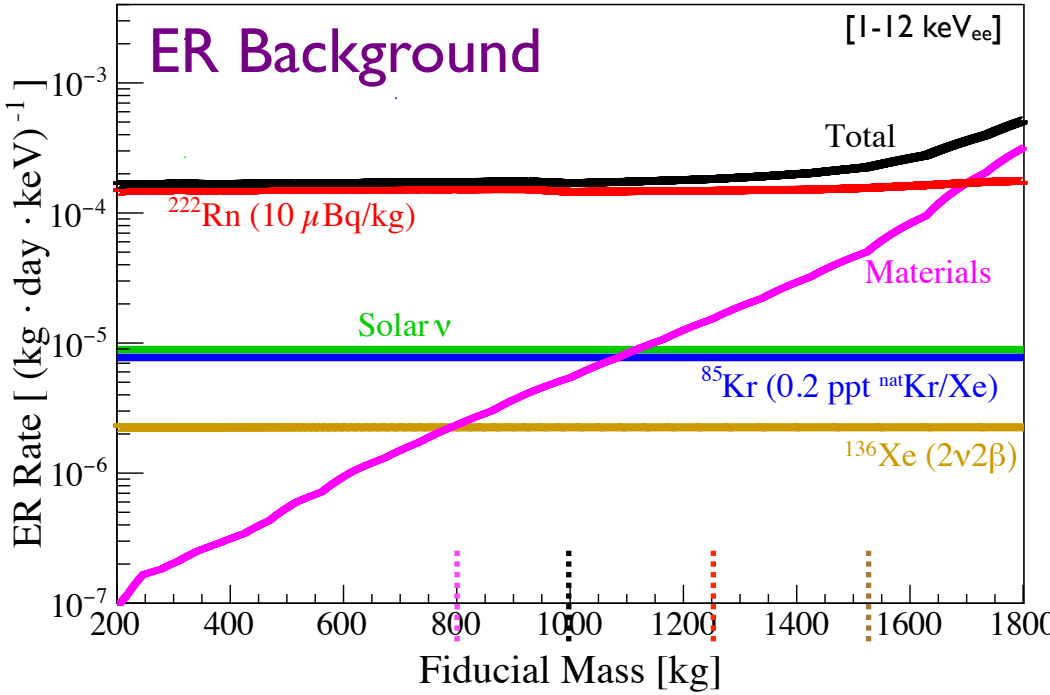


DM Search Region

XENON Coll., arXiv:1512.07501

LXe self-shielding





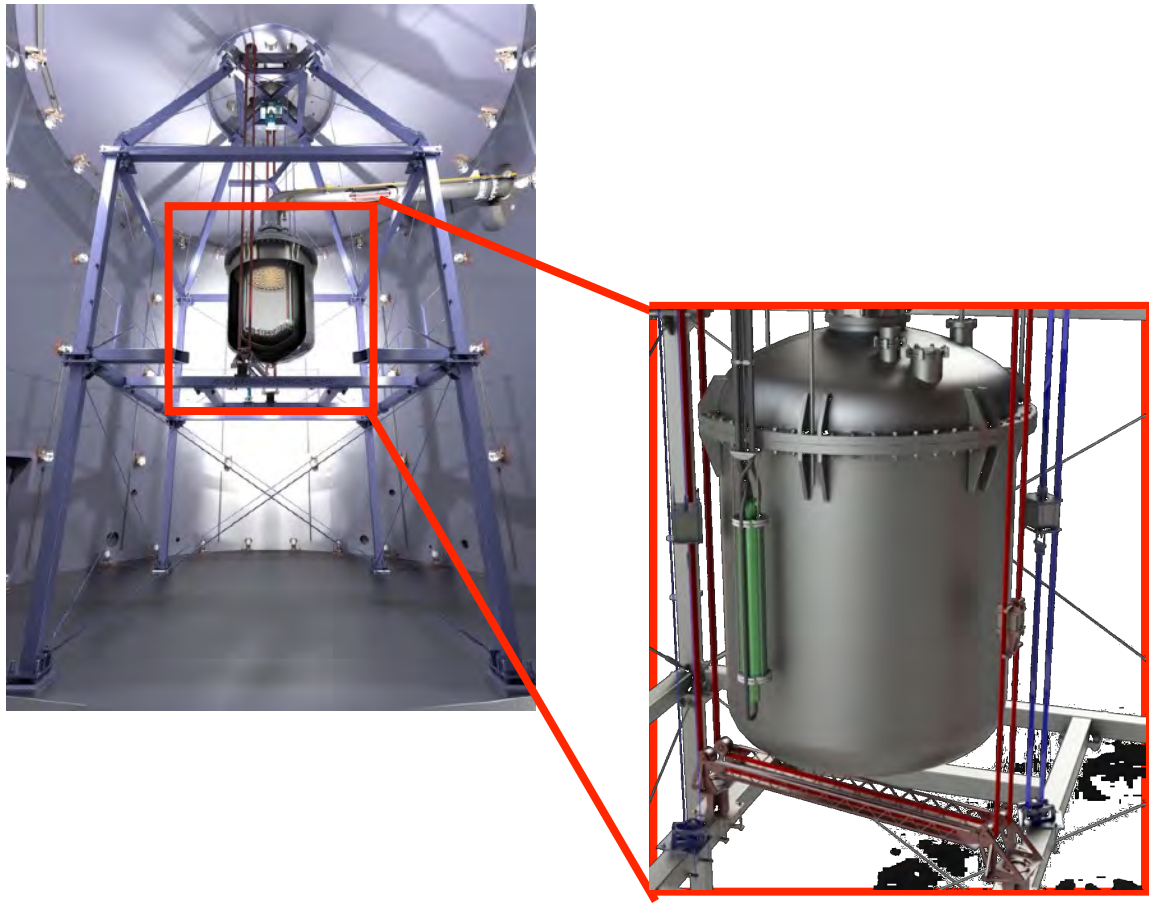
- ER backgrounds from materials are on the surface: fiducial mass cuts effective
- Intensive campaign to select clean materials
- ^{222}Rn is dominant ER BG
- Radiogenic neutrons dominant NR BG

XENON Coll., arXiv:1512.07501

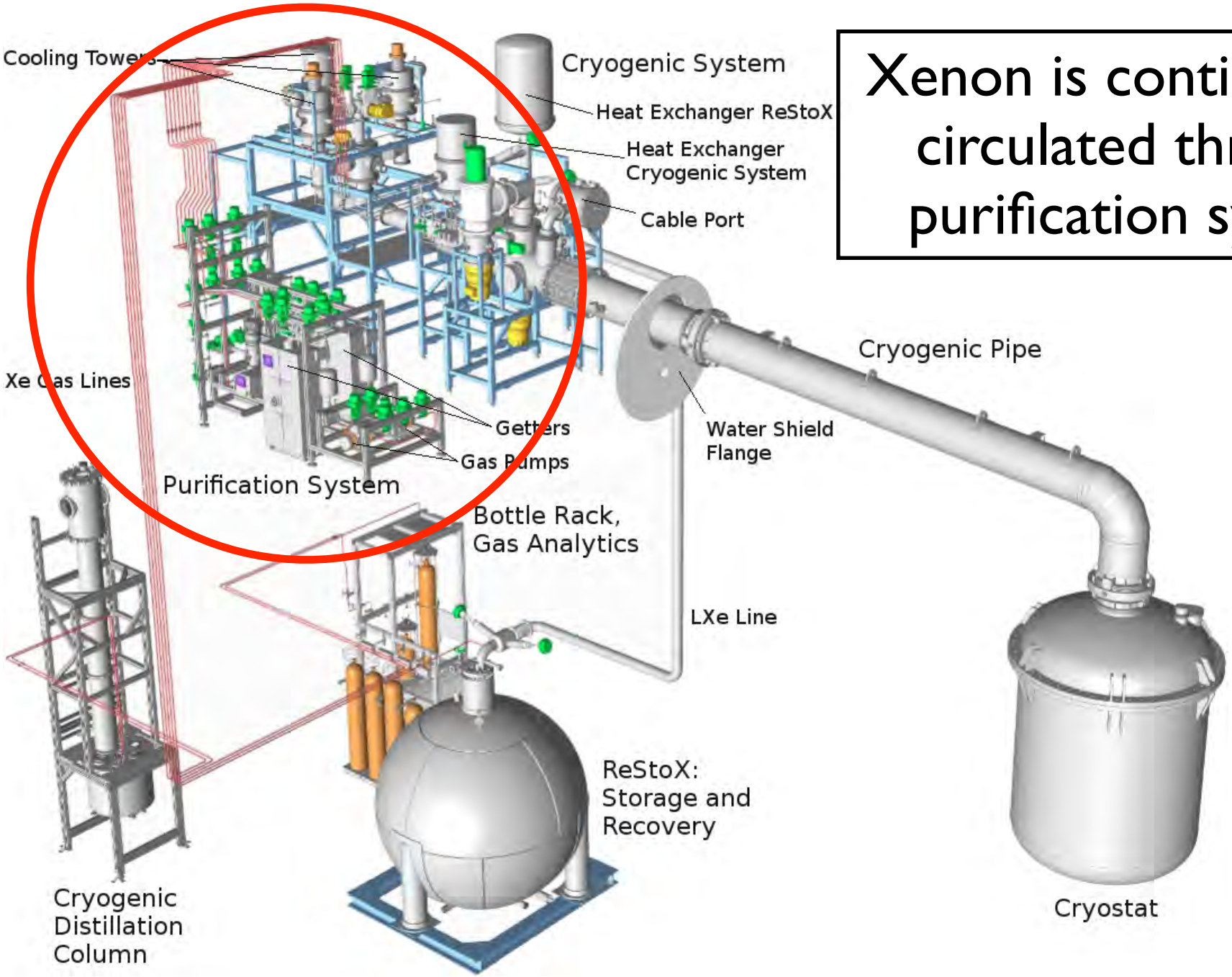
Calibration Systems

- Variety of calibration sources:
  - "Internal" sources: ^{83m}Kr, ^{220}Rn
  - External sources: ^{241}AmBe, neutron generator
  - Materials: ^{60}Co, ^{129m}Xe, ^{131m}Xe

Thesis
Erik Hogenbirk

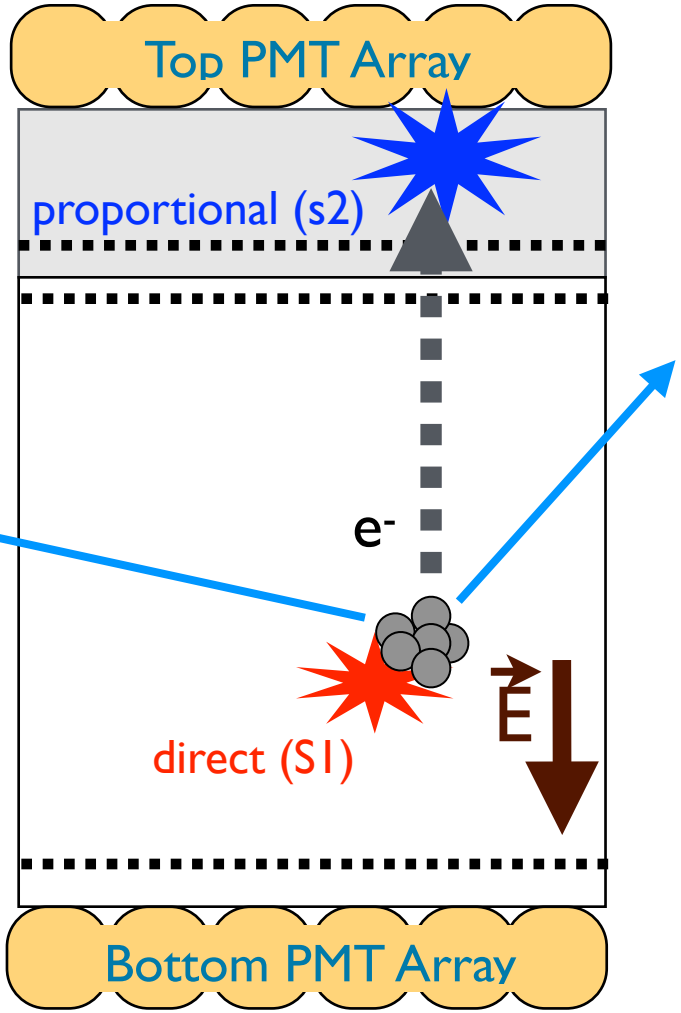


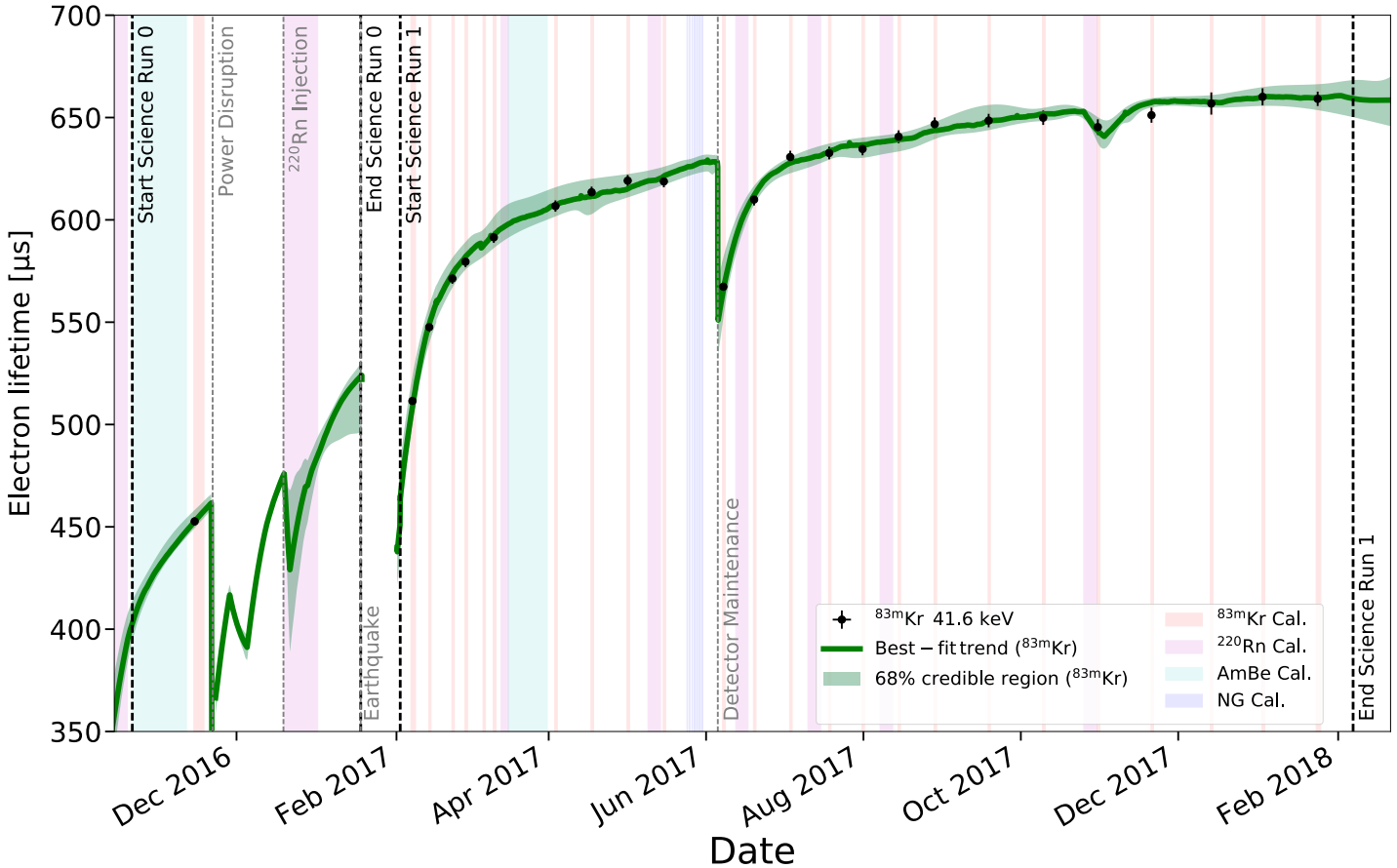
Cryogenic System



Xenon is continuously circulated through purification system

Electron Lifetime

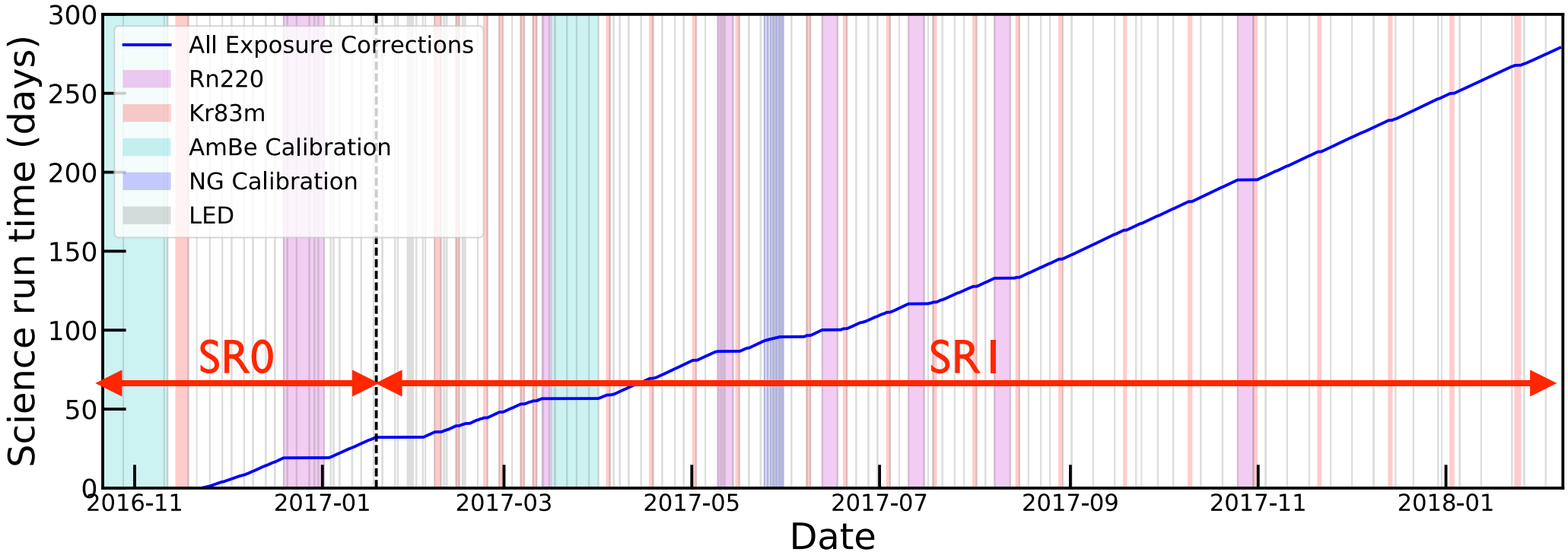




Xenon is continuously purified

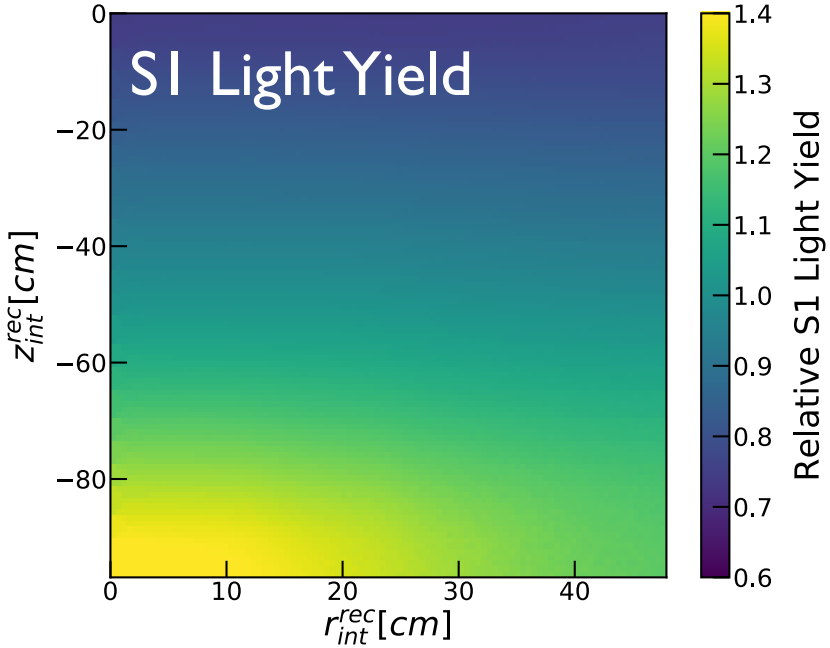
Full drift length is 673 μs

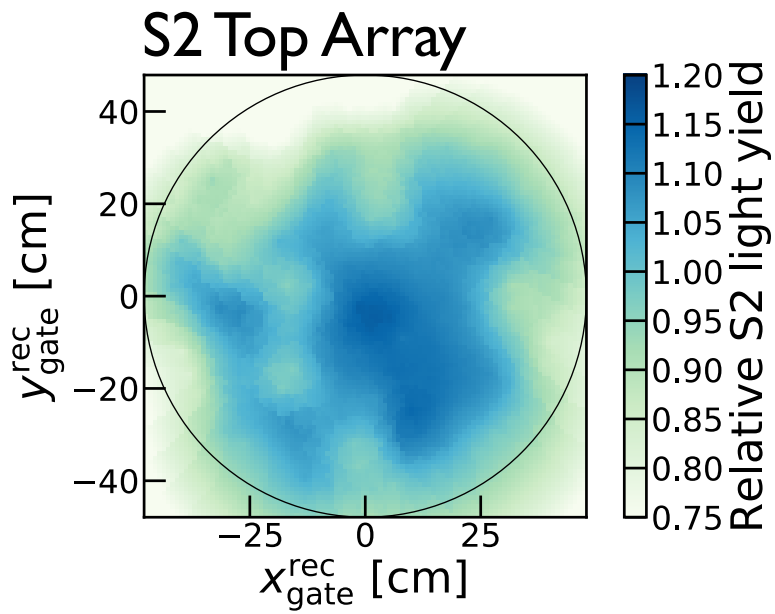
Exposure



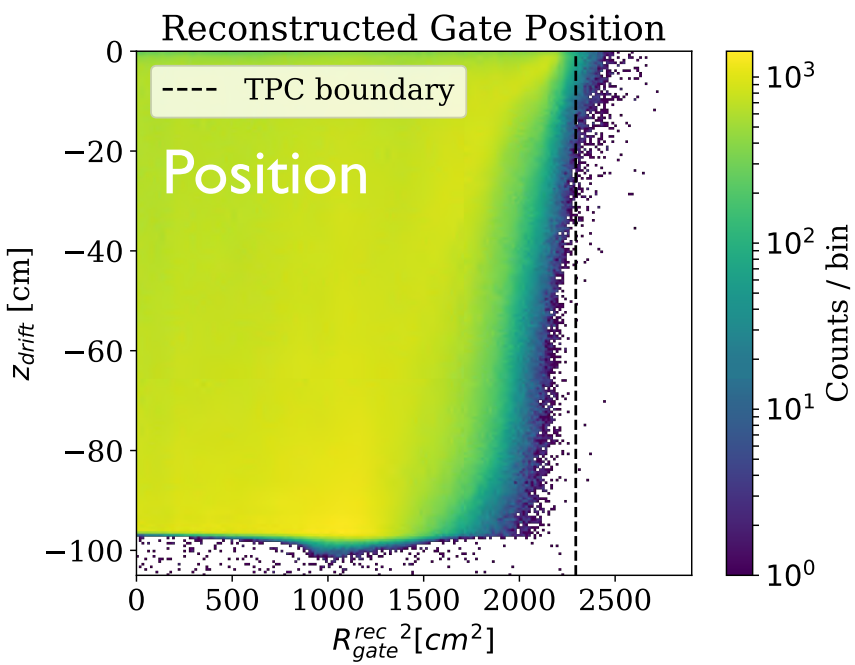
- Detector ran smoothly - DAQ efficiency ~99%
- Two Science Runs: 32 days and 247 days
- About 1 ton-year of exposure accumulated in 1.3 ton fid. volume

Examples of Corrections

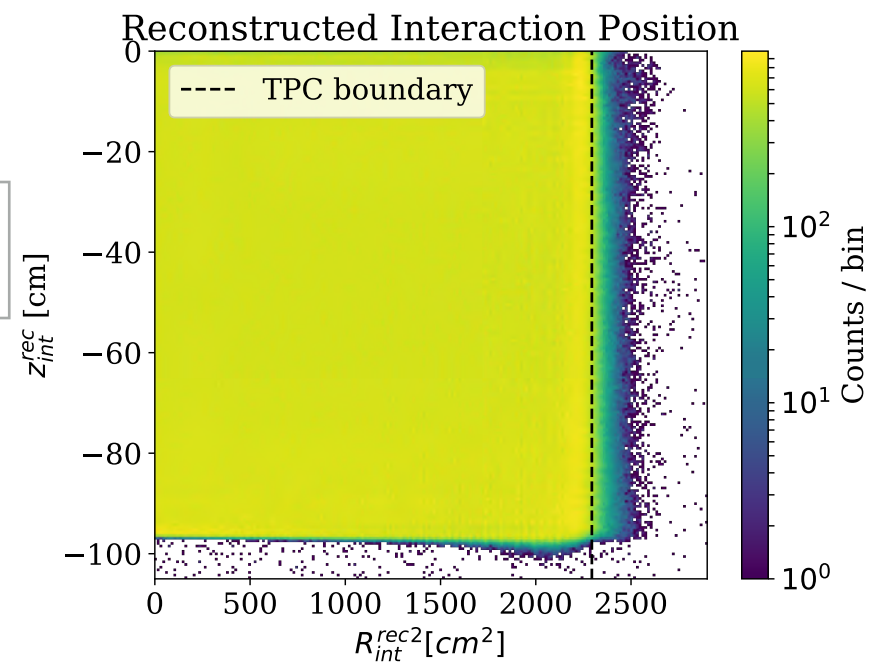




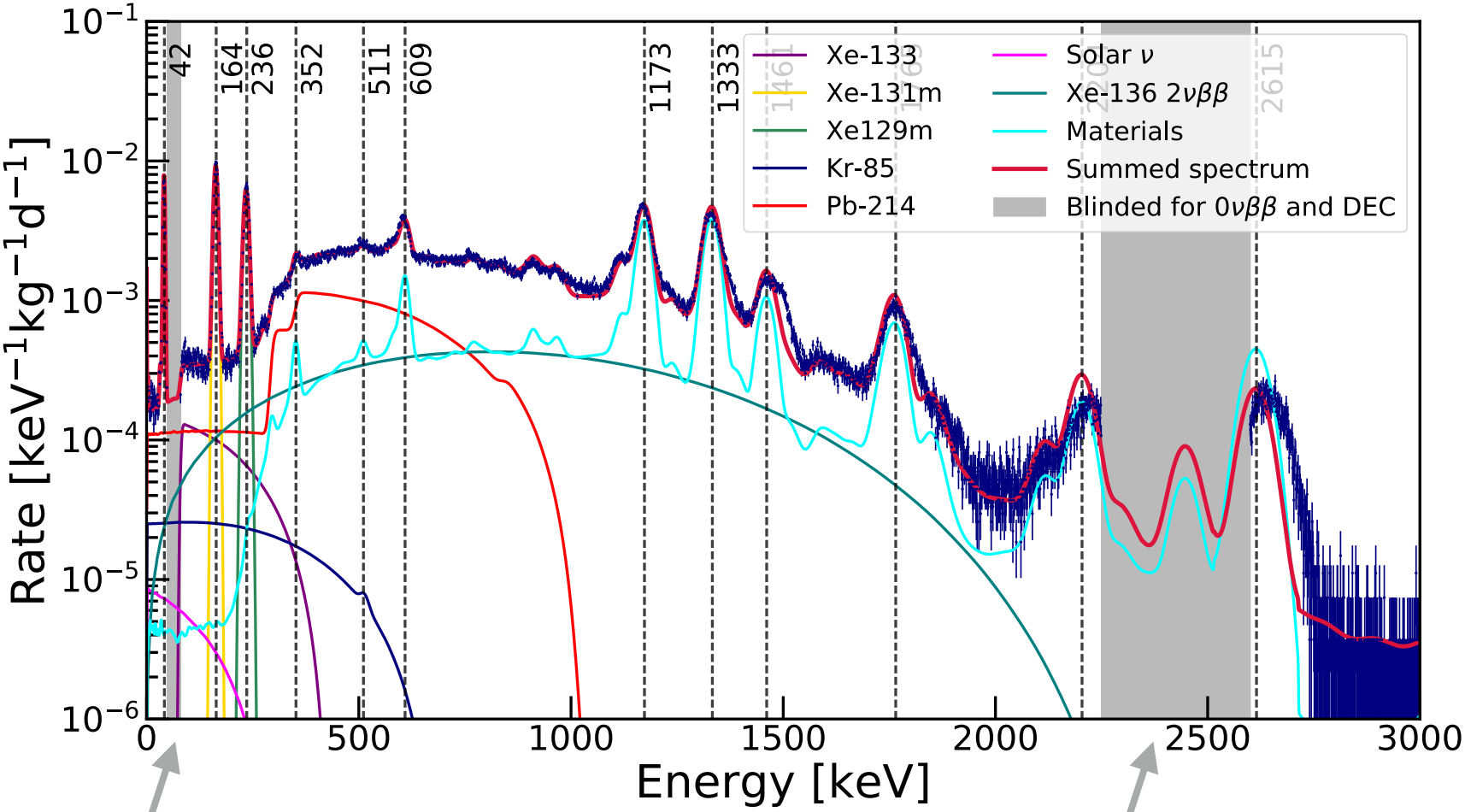
^{83m}Kr calibrations



Correction of E-field distortion



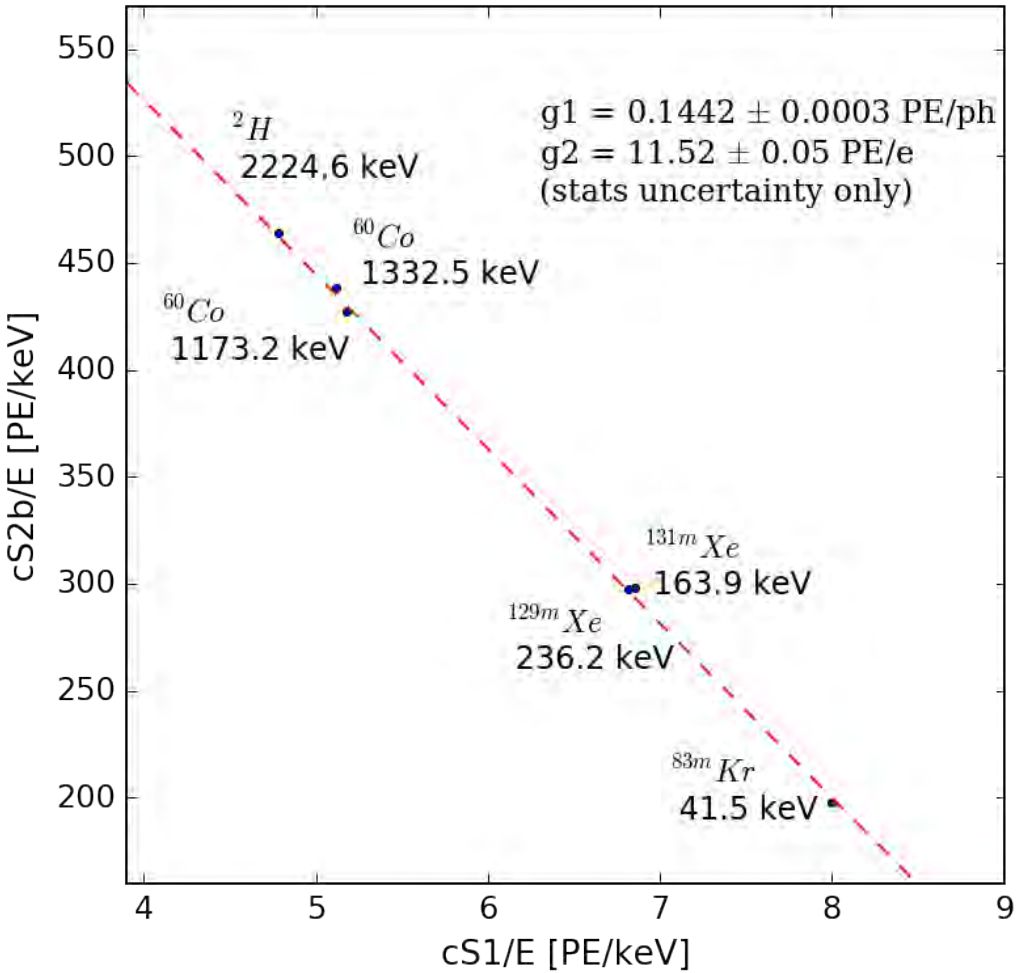
Wide range energy reconstruction



2 E.C. in ^{124}Xe

0ν2β in ^{136}Xe

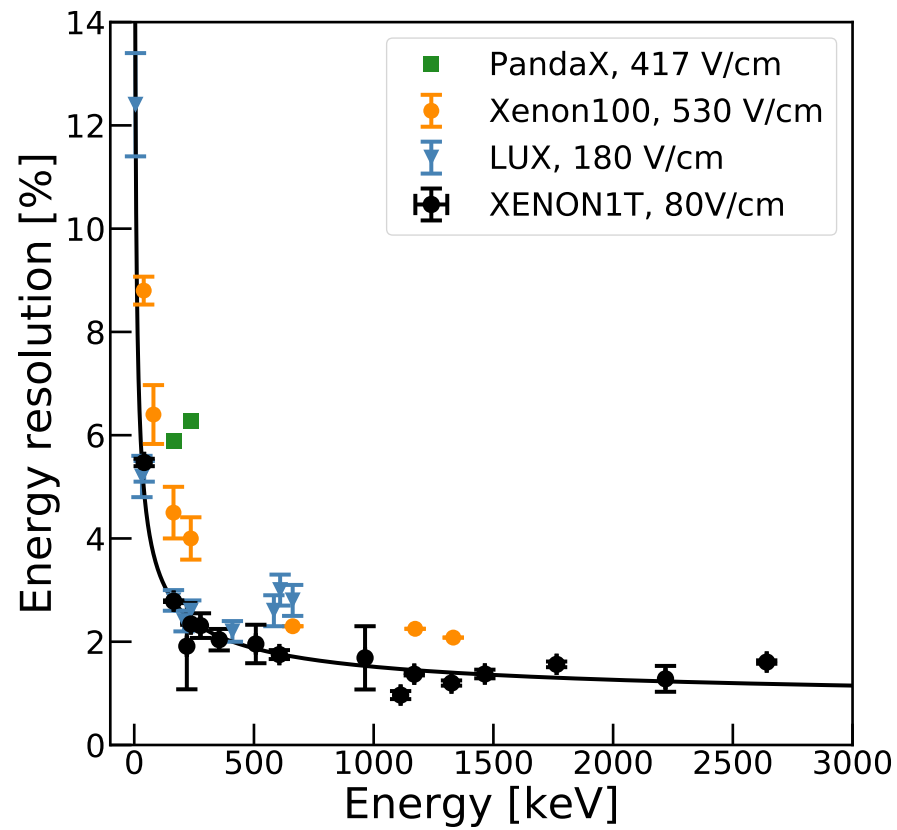
Energy Reconstruction



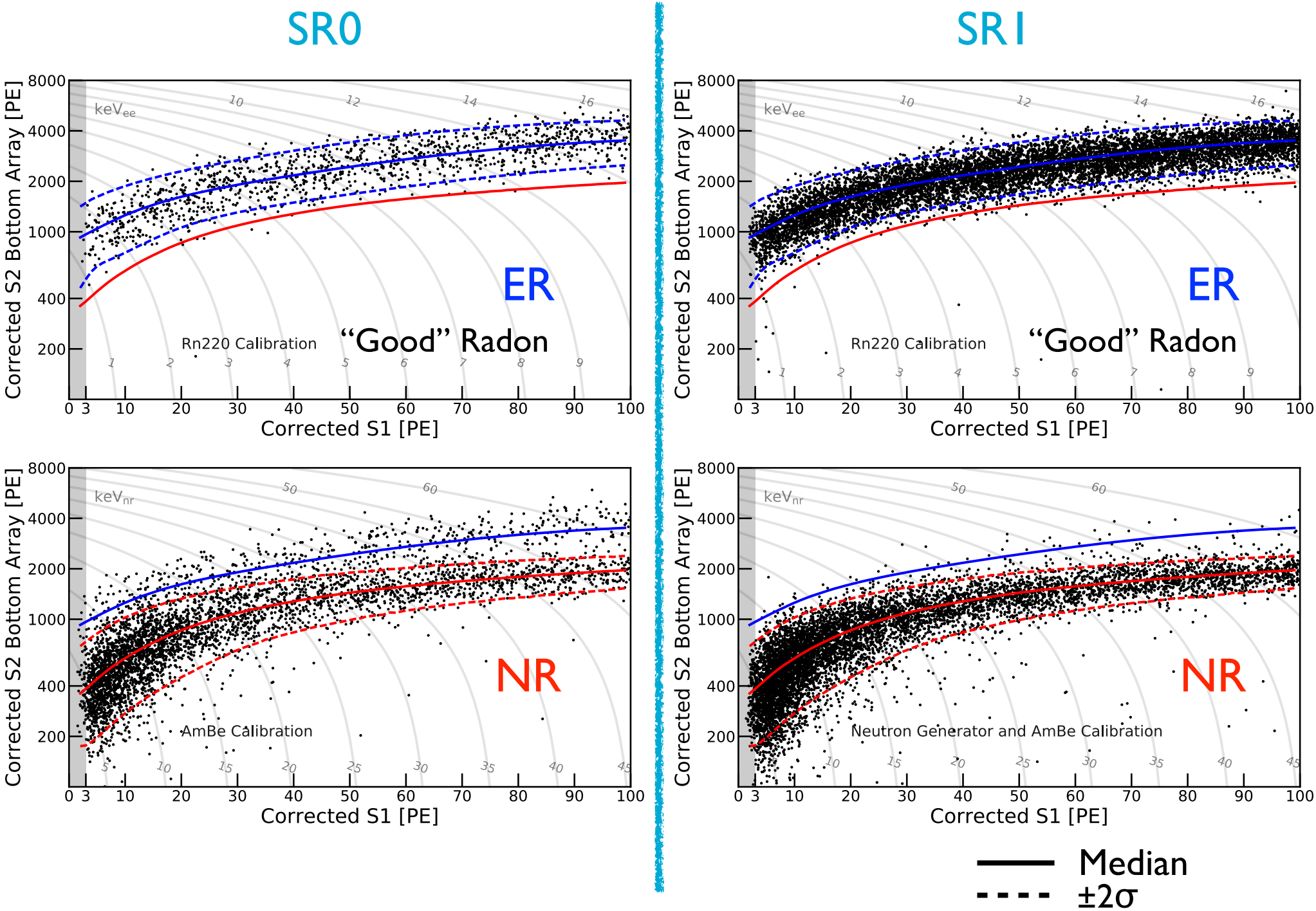
$$E = W \cdot (n_{ph} + n_e) = W \cdot \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$

13.7 ± 0.2 eV

- Parametrized in g1 and g2
  - Detector dependent
- Excellent ER energy reconstruction
  - From 40 keV to 2.2 MeV



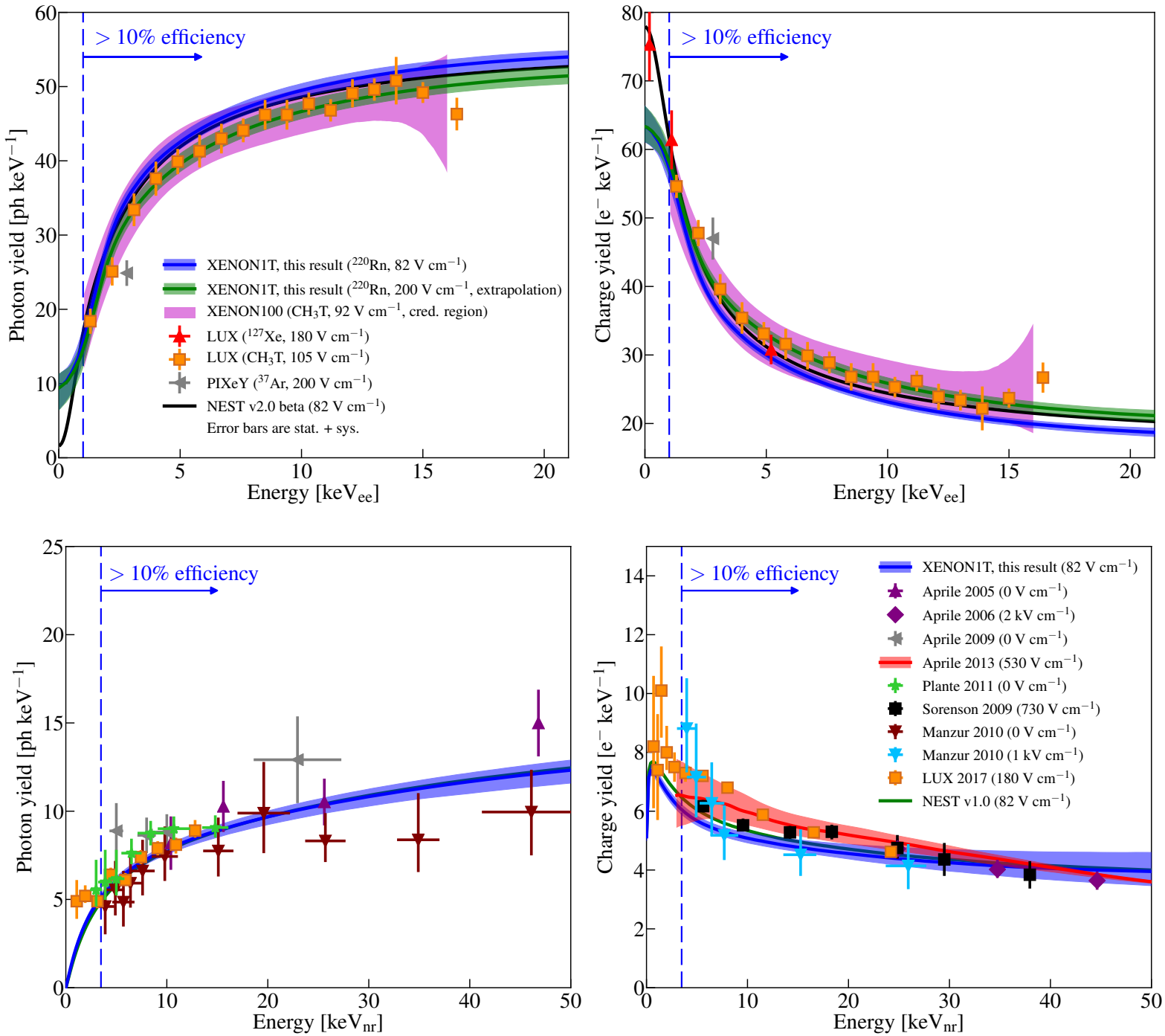
Improved calibration statistics



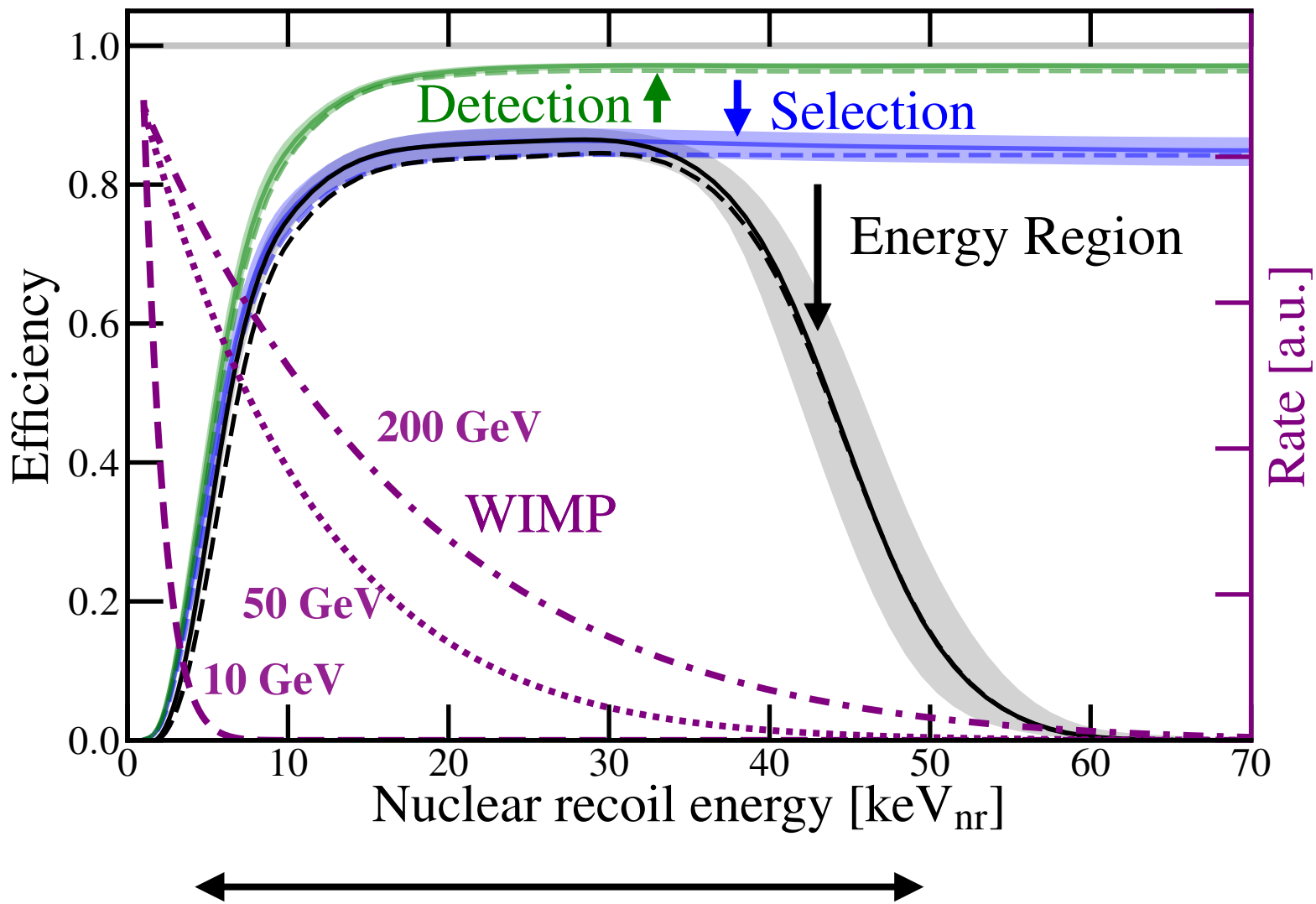
Detailed Response Model of detector

ER

NR



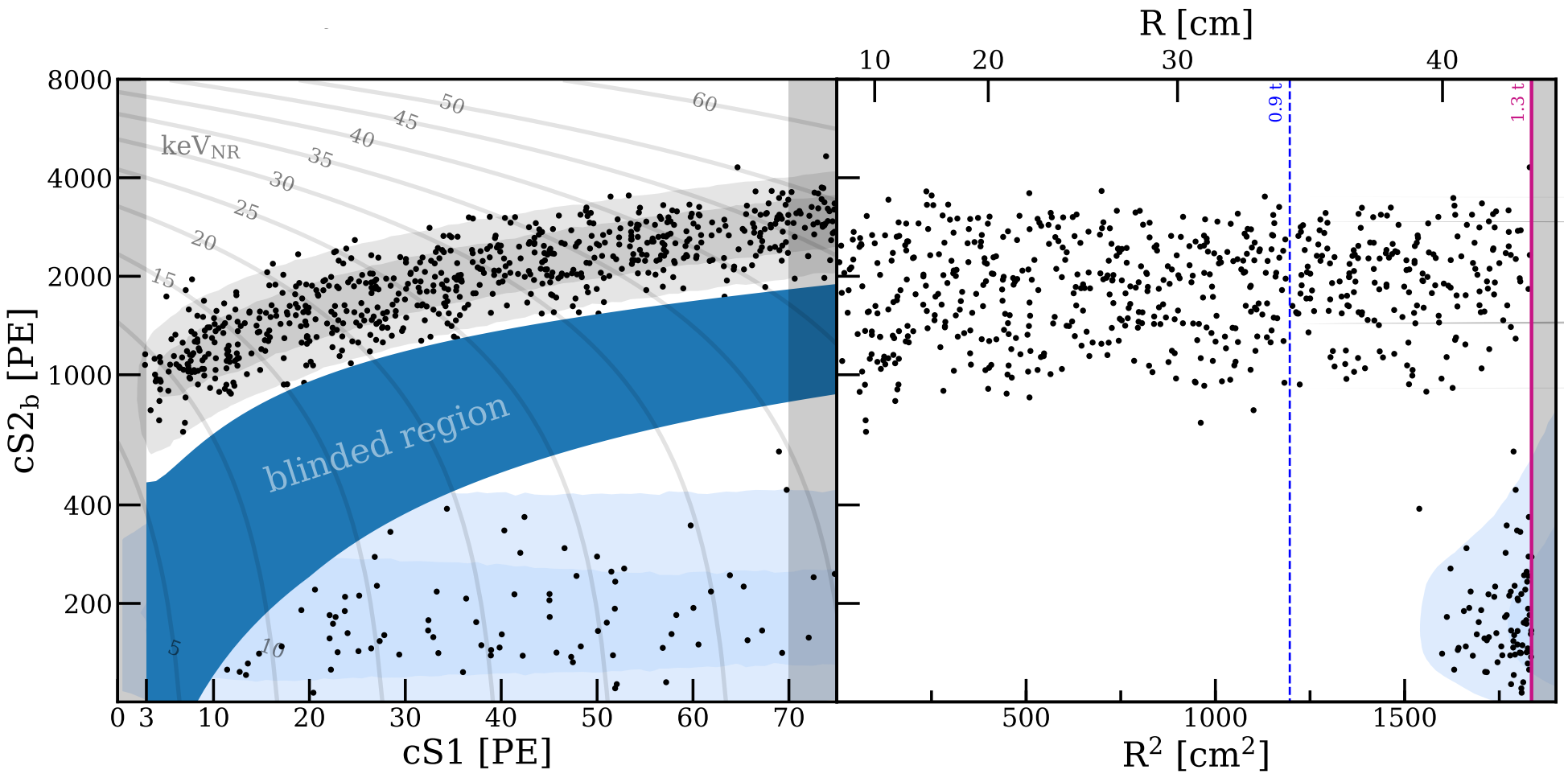
Efficiency


Detection
Selection
Energy Region
200 GeV
WIMP
50 GeV
10 GeV
Efficiency
Rate [a.u.]
Nuclear recoil energy [keV$_{nr}$]
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70

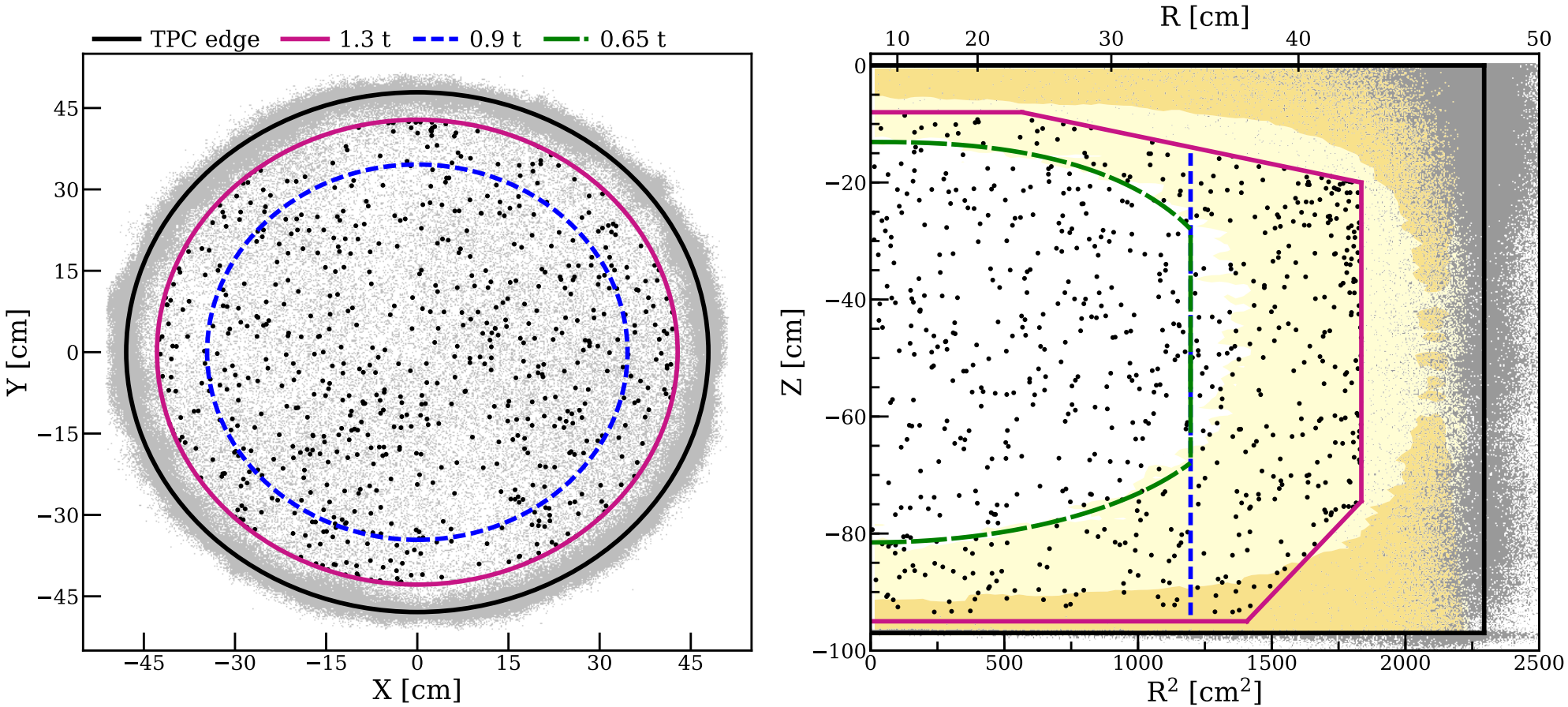
WIMP Search Region

ROI: 3PE < S1 < 70PE
equiv: ER: 1.4 - 10.6 keV_{ee}
NR: 4.9 - 40.9 keV_{nr}

Analysis was:
Blinded
"Salted"

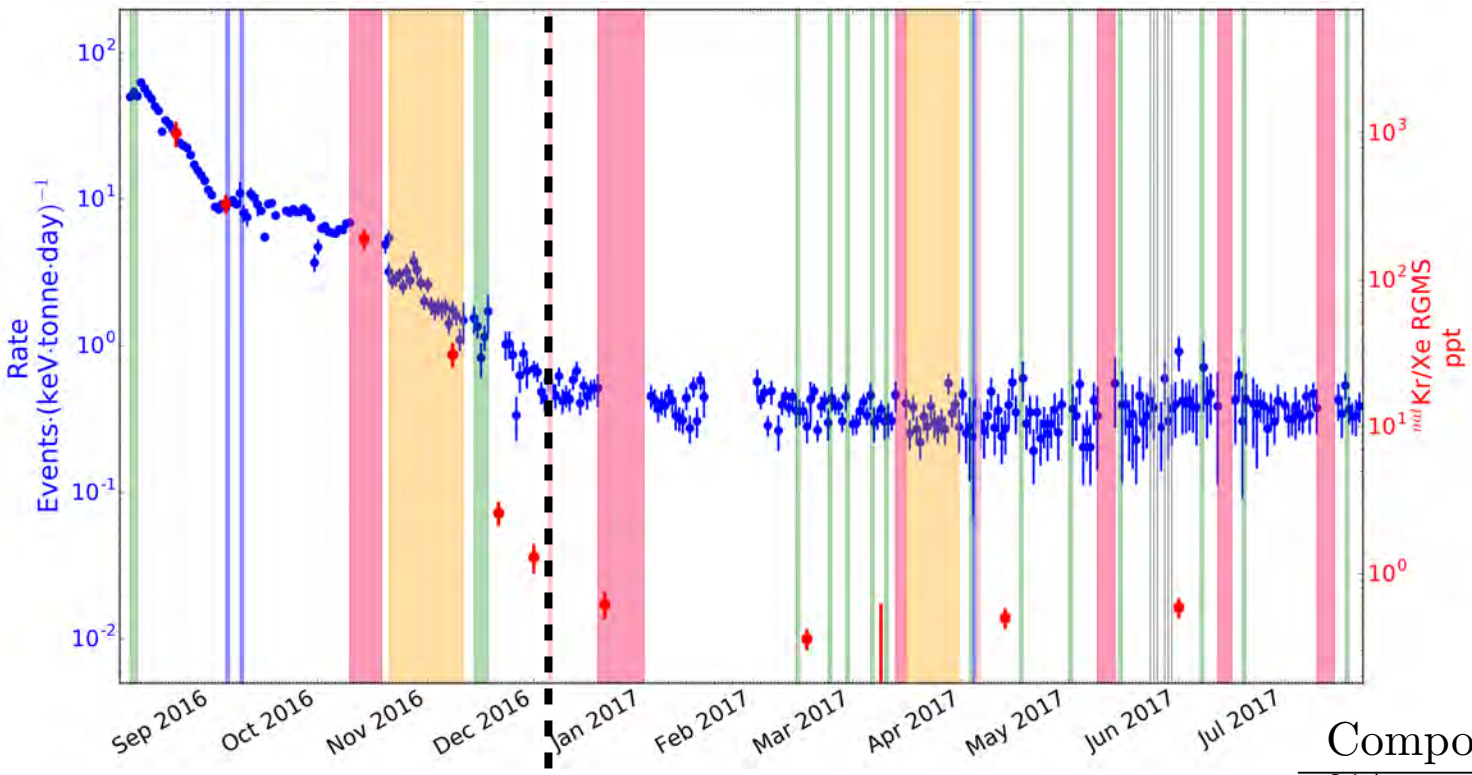


Fiducial mass Selection



- Signal and background are modeled in (cS1, cS2, R, "z") space
- Fiducial mass increased from 1 ton → 1.3 tons
- Total exposure of SR0+SR1: 1 ton x year

Ultra Low ER Background



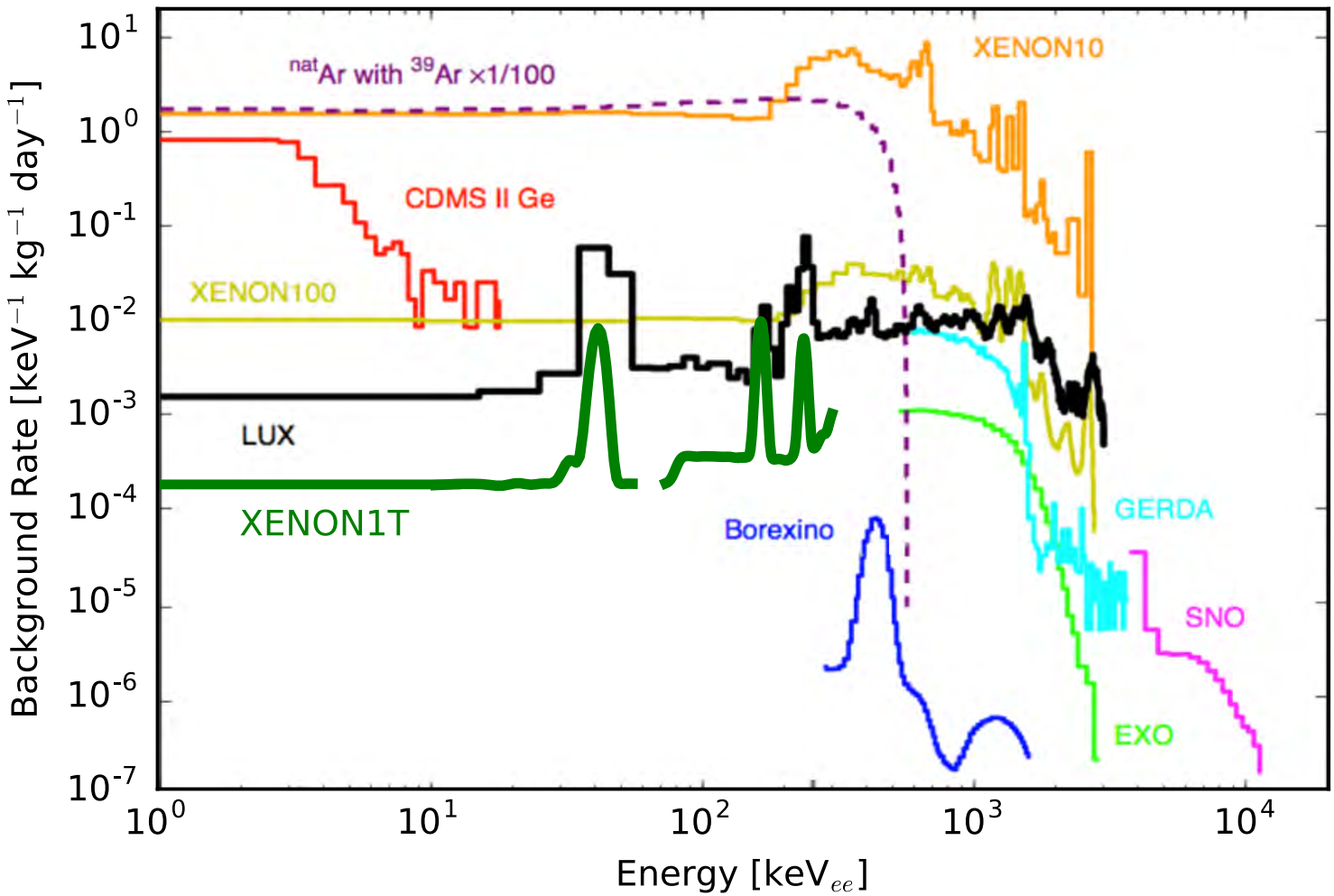
- ^{85}Kr: ^{85}Kr/^{nat}Kr ~10^{-11}

Component	ER rate [ev/(keV$_{ee}$ · t · yr))]
^{214}Pb	56 ± 6
^{85}Kr	7.7 ± 1.3
Materials	8 ± 1
Solar ν	2.5 ± 0.1
^{136}Xe $2\nu2\beta$	0.8 ± 0.1
Total pred. MC	75 ± 6
Measured	$82^{+5}_{-3}(\text{syst})\pm3(\text{stat})$

- ER rate initially dominated by ^{85}Kr
- Distilled out - remainder is due to ^{222}Rn decay "Bad" Radon
- Measured BG: (82 ± 5) events/(keV$_{ee}$ x yr x t)
- **Lowest ever achieved in a dark matter detector!**

Thesis
Sander Breur

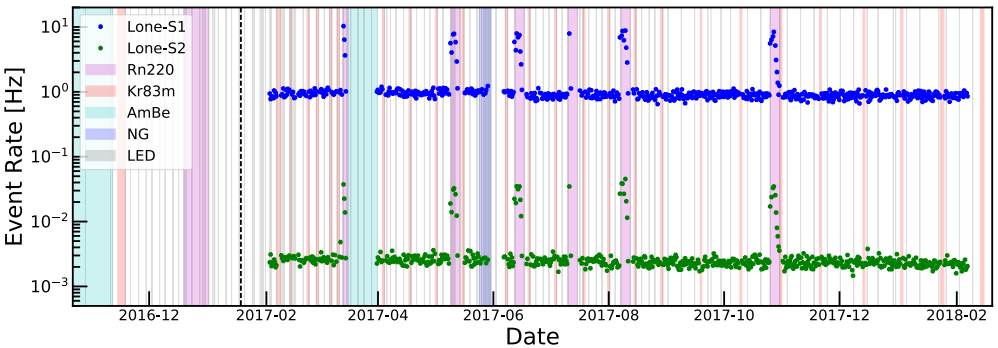
Lowest Background of any DM experiment

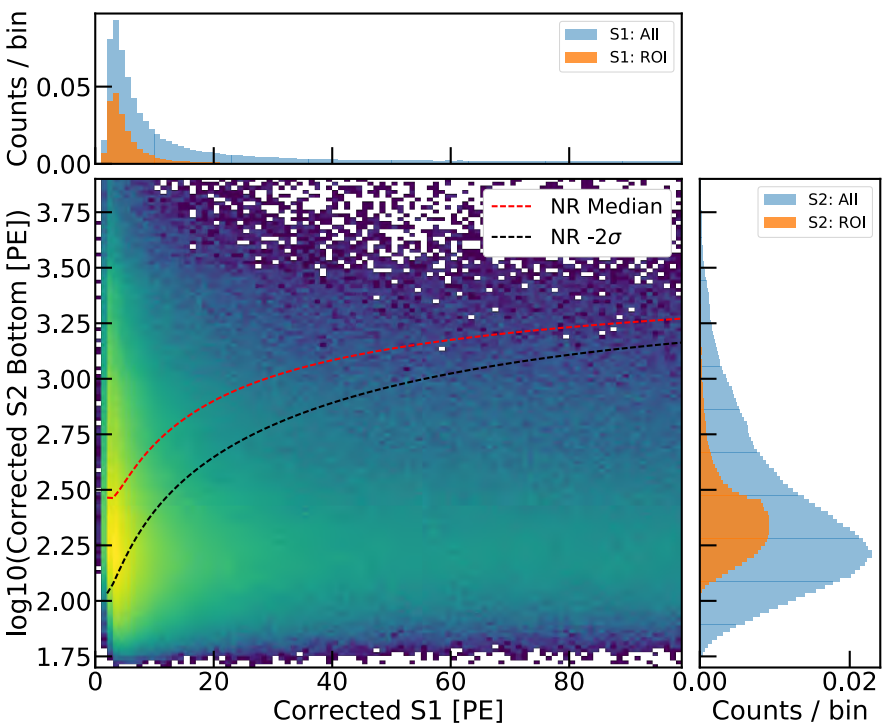


Thesis
Sander Breur

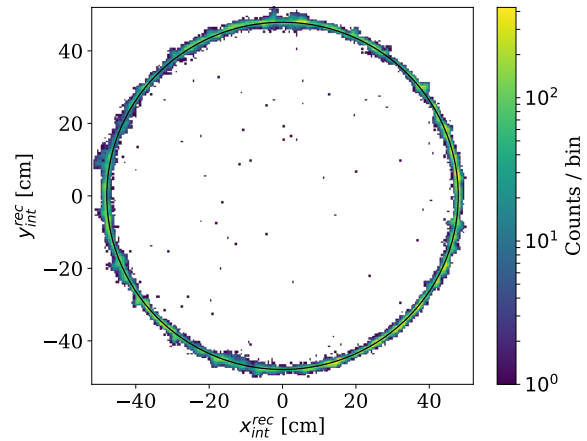
Accidental + Surface Backgrounds

Accidental Background



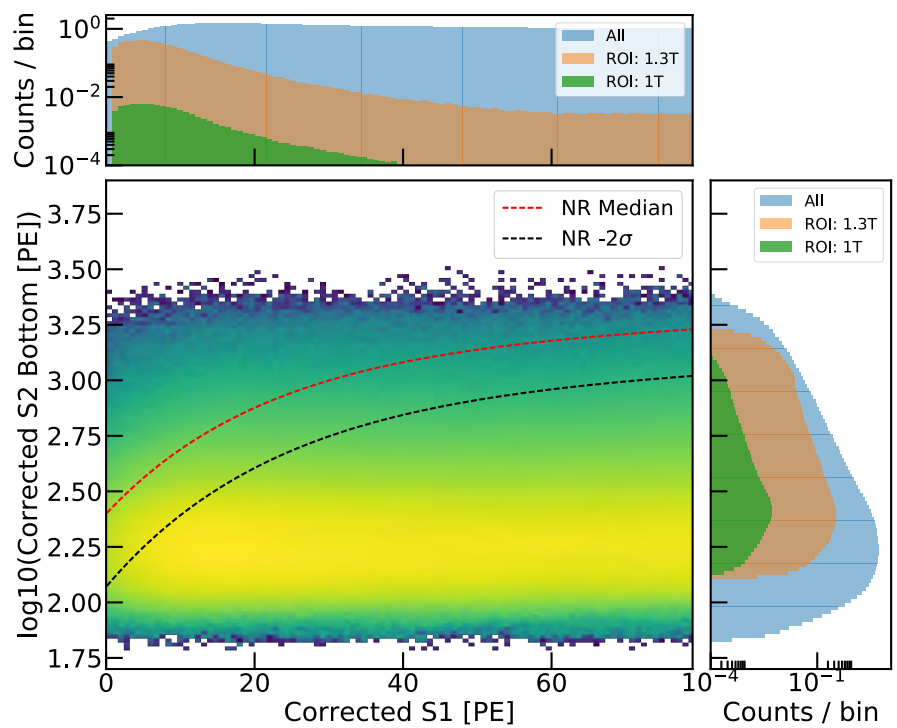


Surface Background



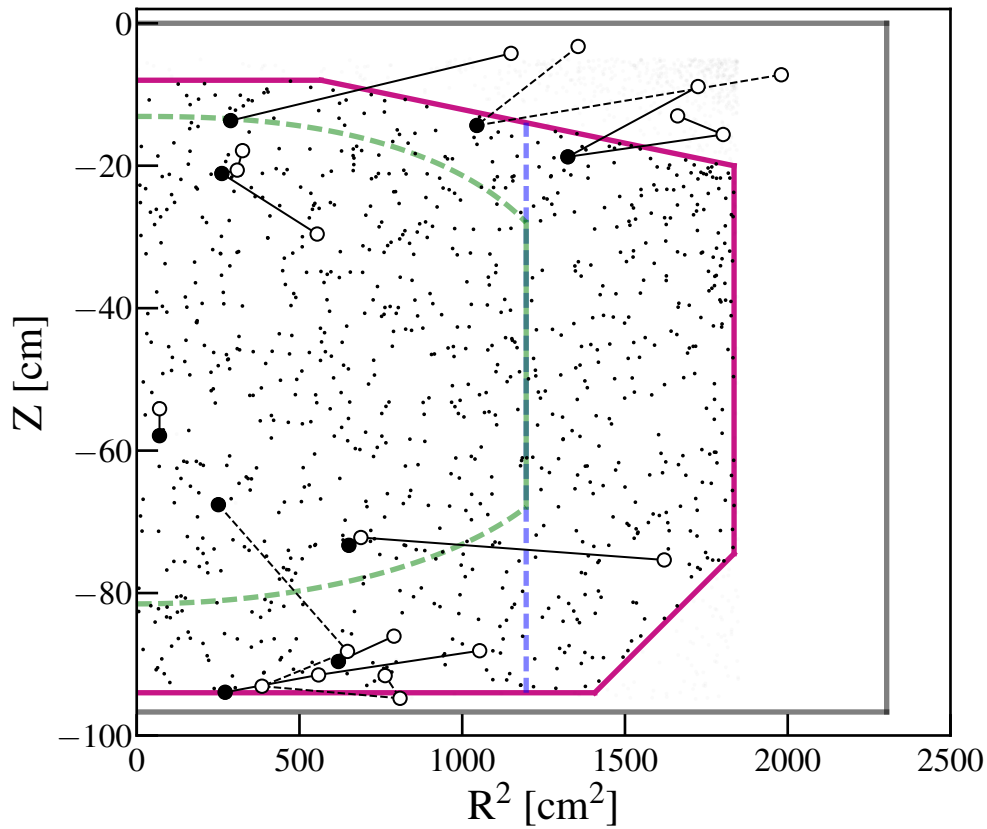
Thesis S.Breur

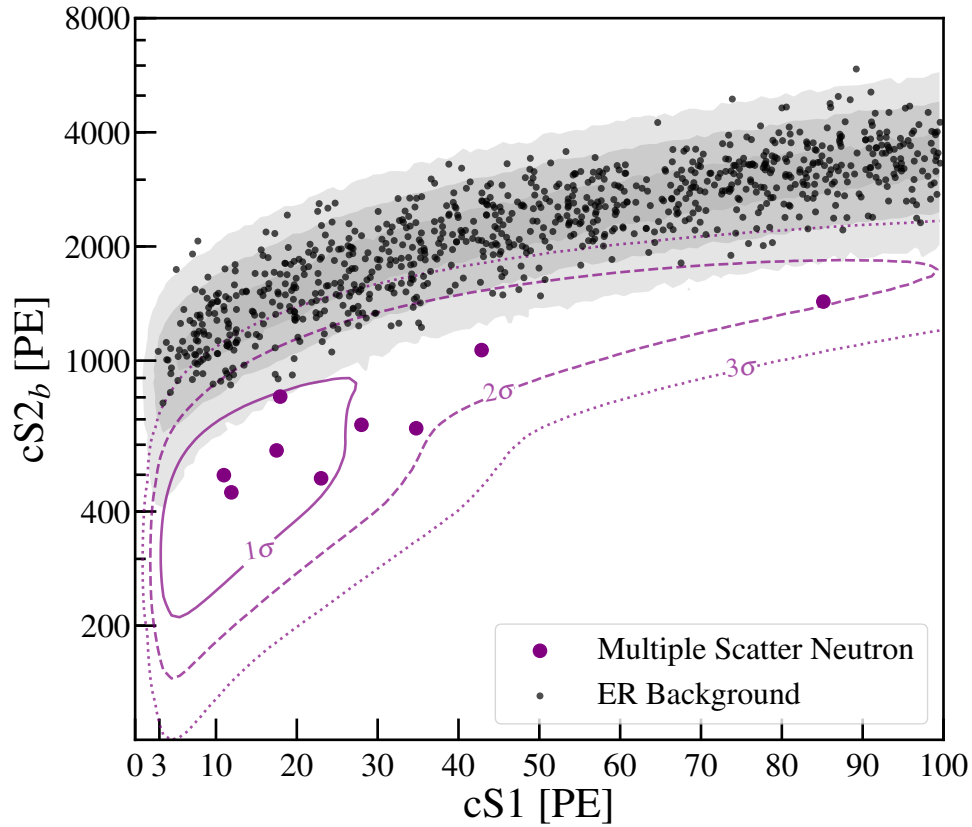
Plate out of ^{210}Po and incomplete charge (S2) collection



NR Background

Neutrons will multiple scatter in LXe - WIMPs will not



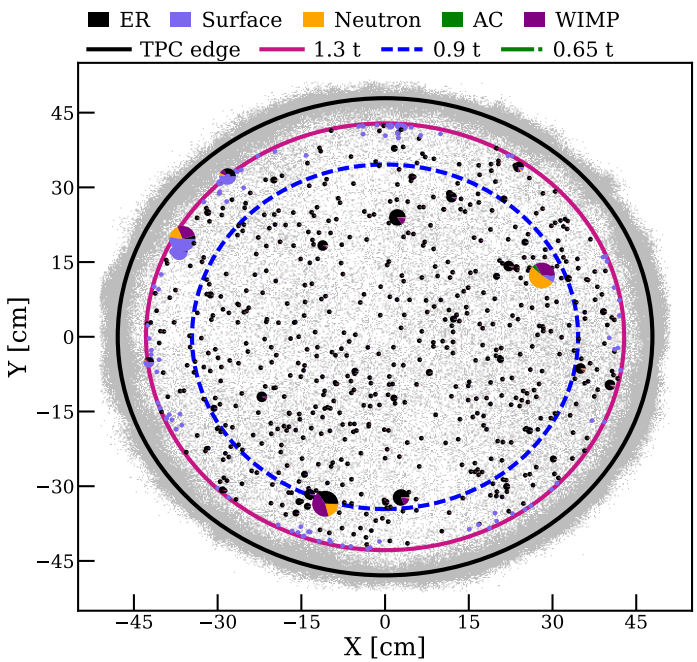


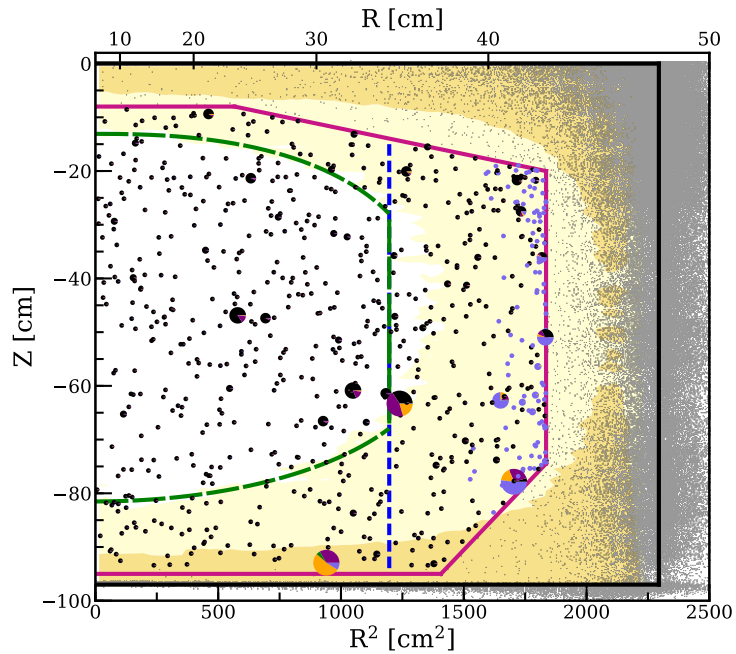
Validation of NR model

Component	NR rate [ev/(t · yr))]
Radiogenic n	0.6 ± 0.1
CNNS	0.012
Cosmogenic	<0.01

1 ton FV

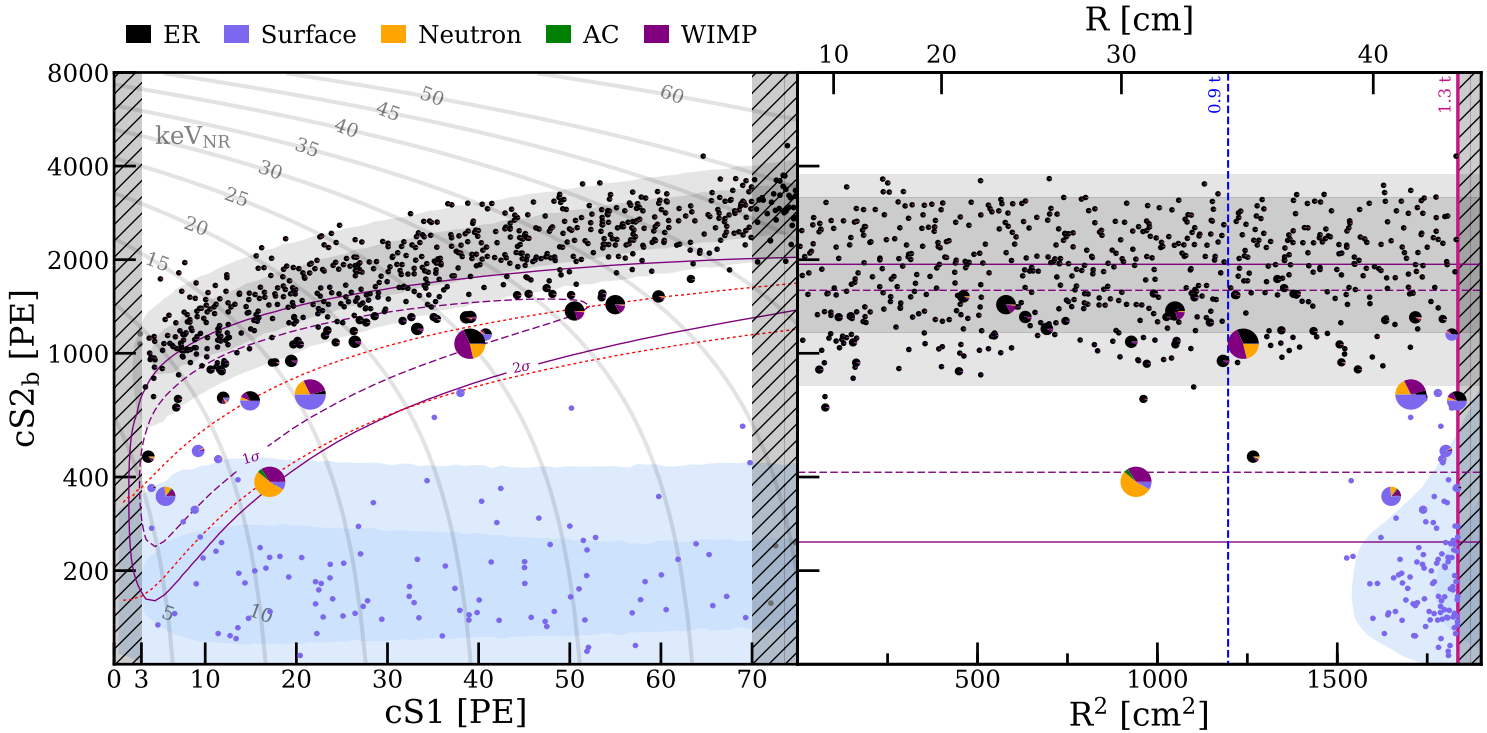
Results after unblinding + unsalting





Had to make post-unblinding changes to BG model and Fiducial Mass segmentation: 2% (4%) increase in final limit (med. sens.)

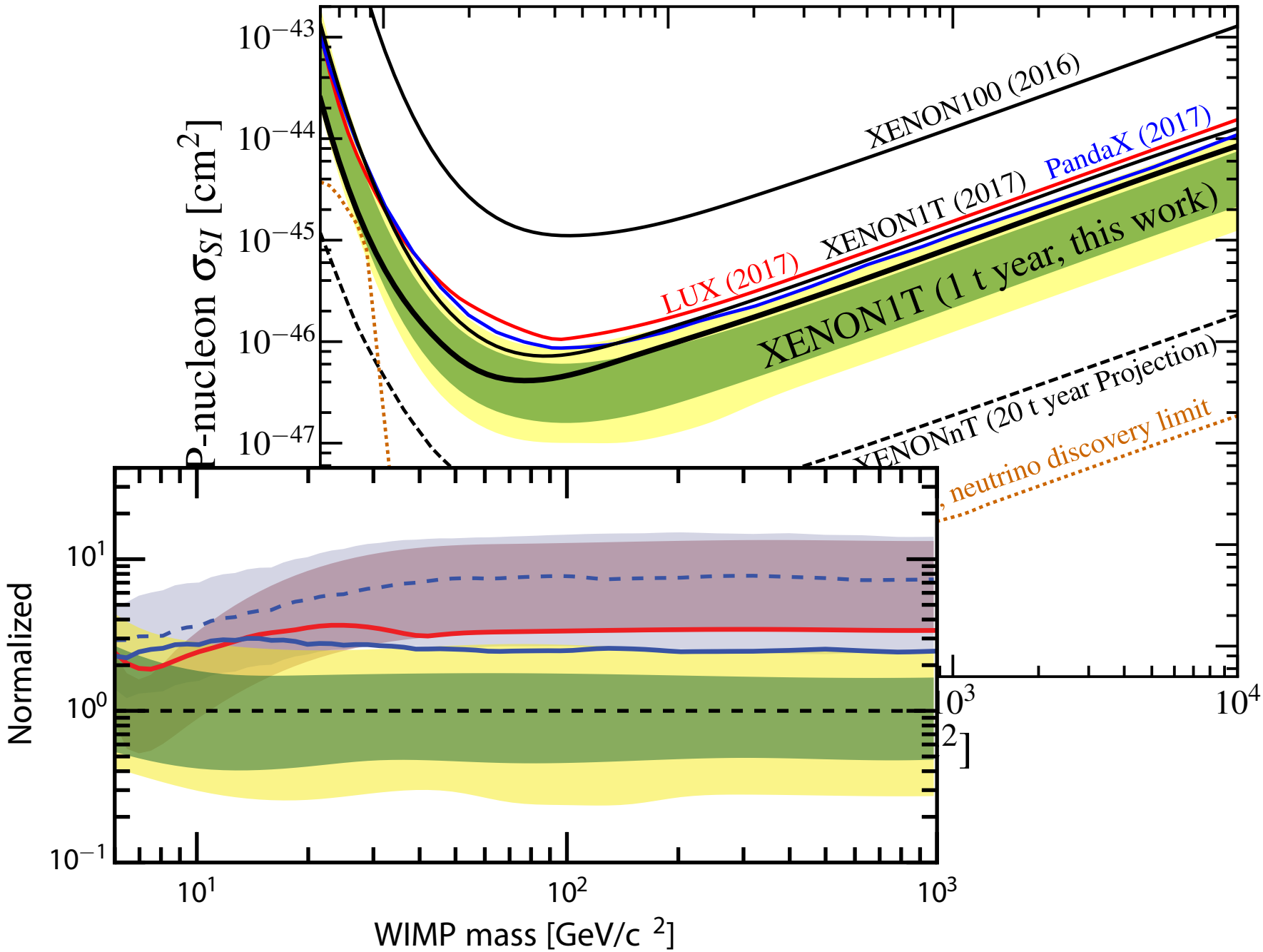
Pie charts:
events passing all cuts, rel. prob. of BG and signal, assuming 200GeV WIMP



Ref NR region

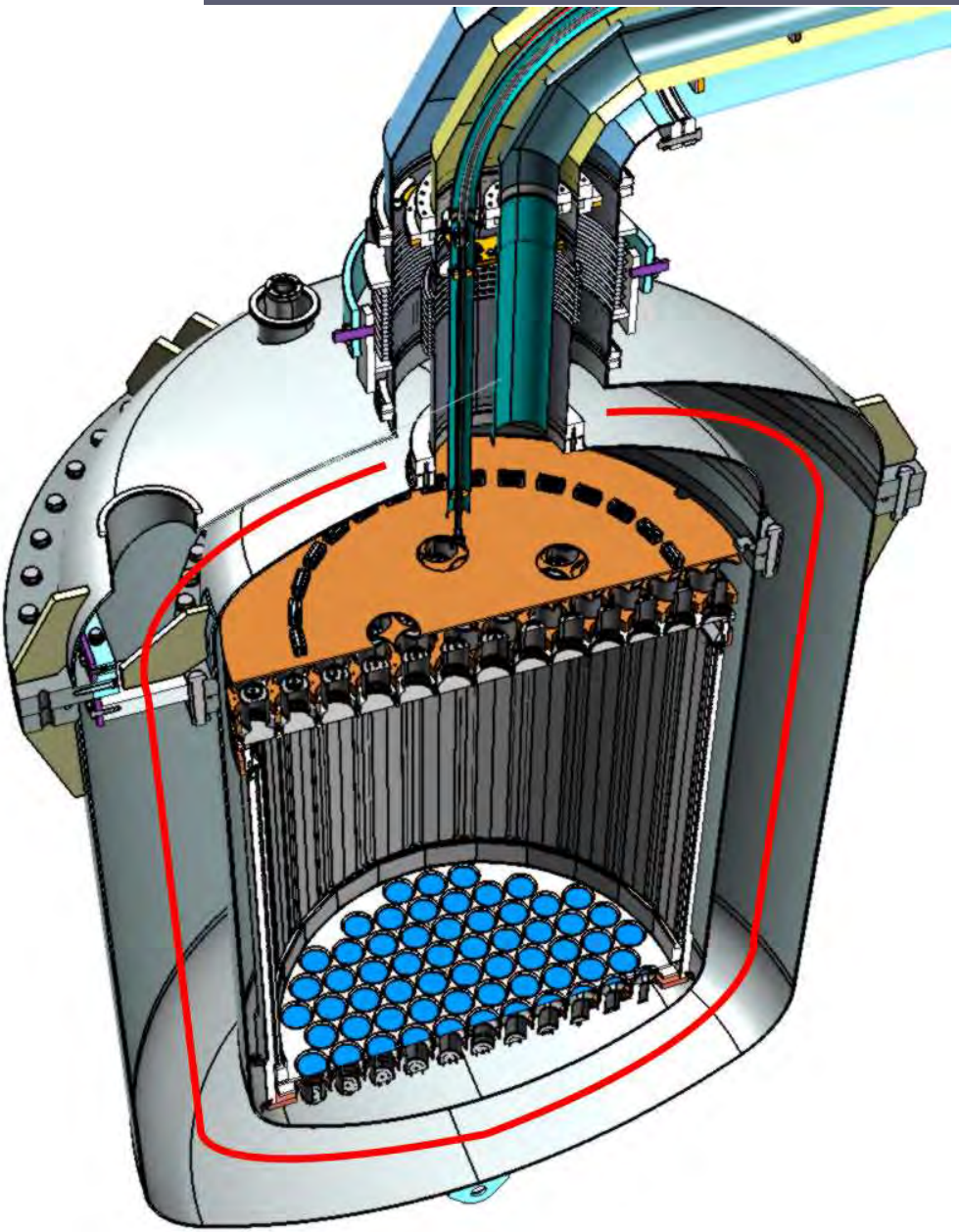
200 GeV WIMP (for illustration)

Final limits from XENON1T

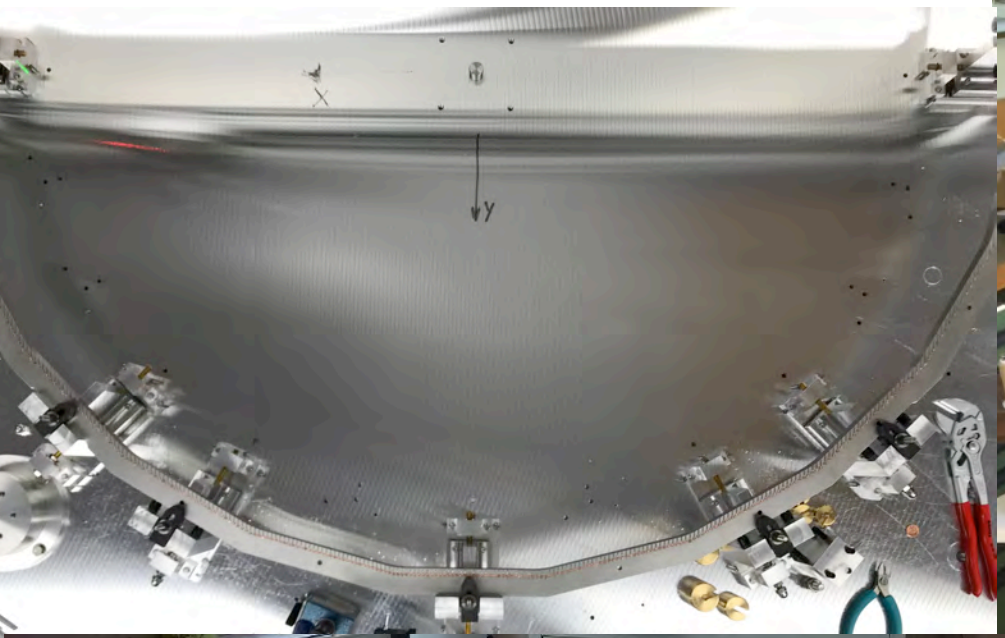


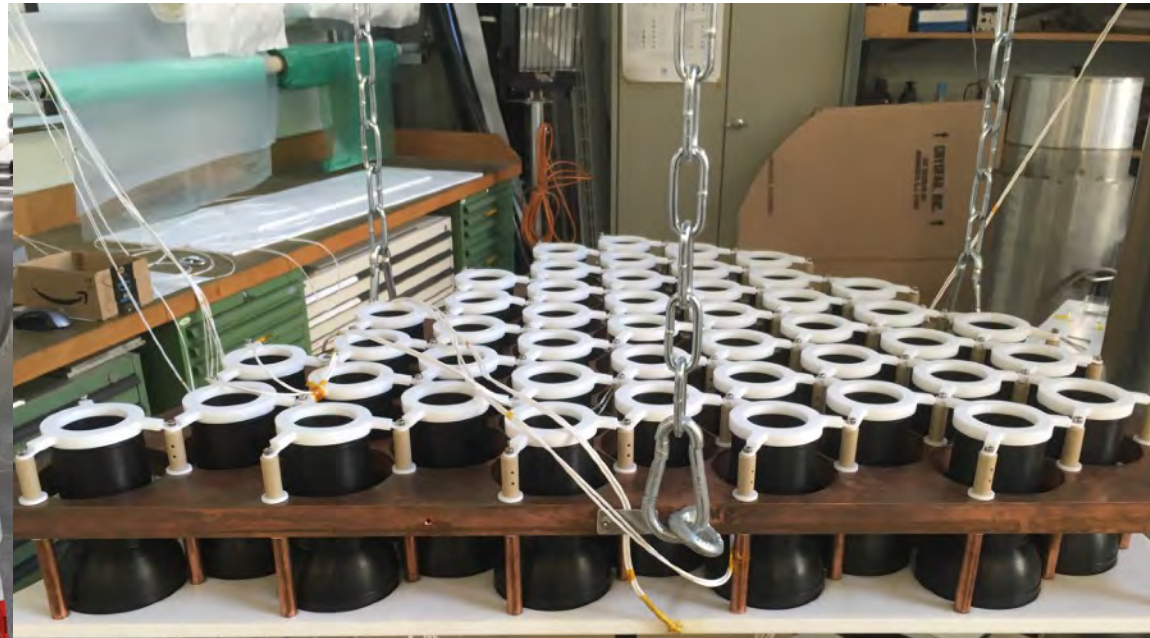
PRL 121, 111302, arXiv:1805.12562

From XENON1T to XENONnT

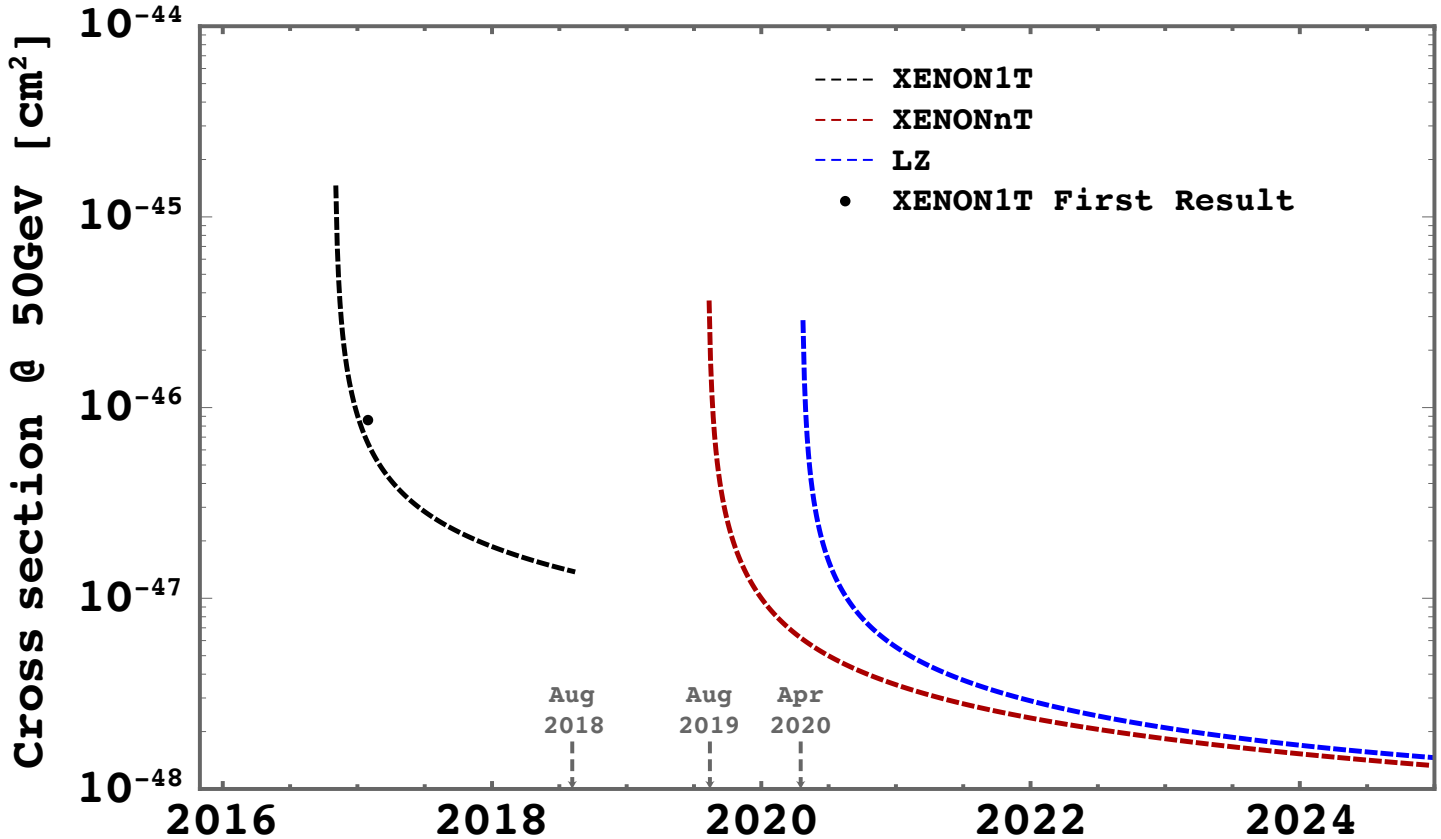


- Reuse most of XENON1T
- Larger inner cryostat vessel
- New TPC
- Additional ~250 PMTs (~500 total)
- Total of ~8 tons of LXe
- Funding complete
- Detector being built / designed
- Start in 2019


X
Y



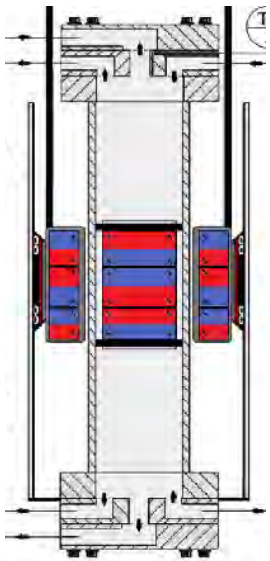
Our XENONnT Goal

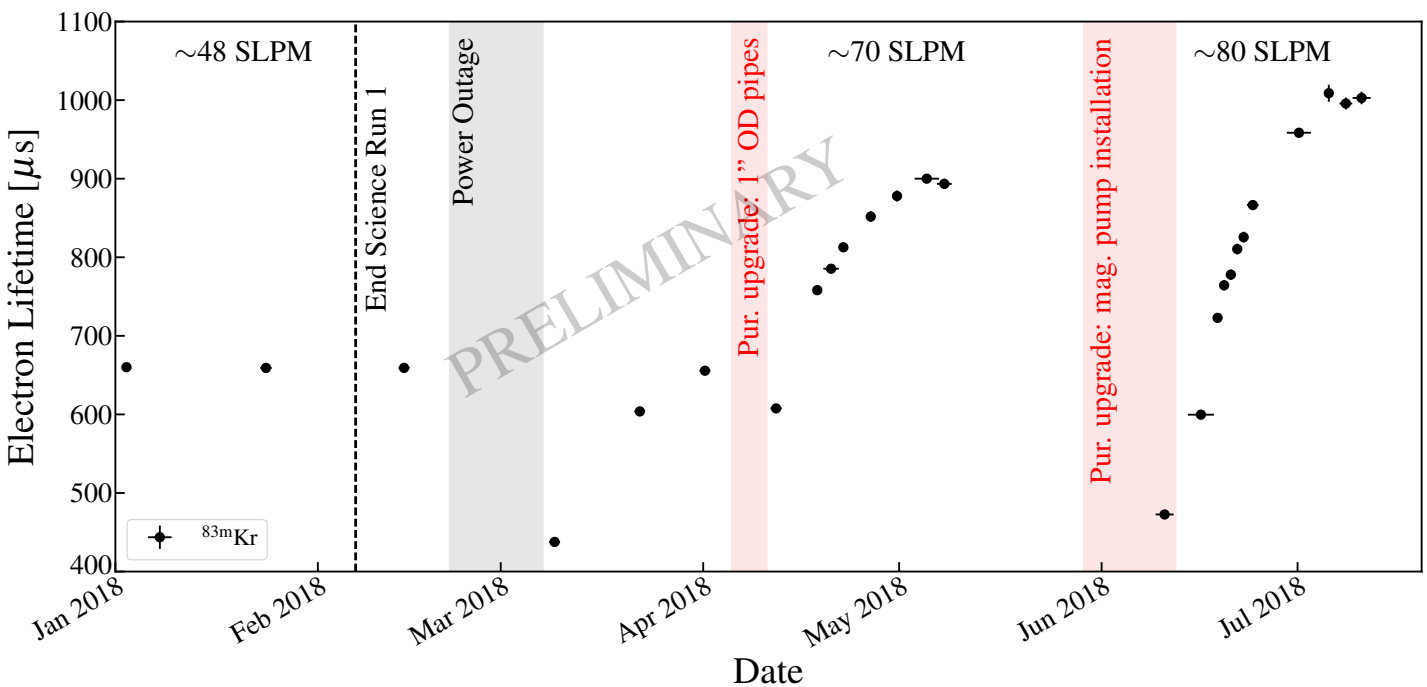


- Increase Xe mass by 3x
- Reduce ^{222}Rn background by 10x
- Veto the ultimate neutron background
- Complement continuous gas purification by liquid purification

New Magnetic Pump

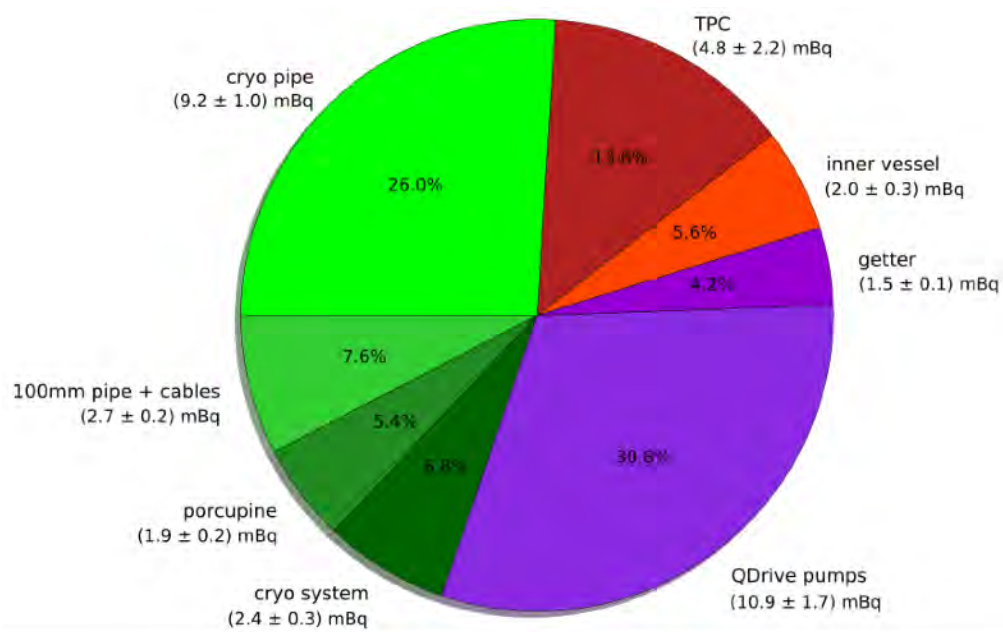
- XENONnT R&D on XENON1T
- New Magnetic Pump
  - Increase LXe purity - longer drift
  - Reduce 222Rn contamination (from emanation of pump materials)

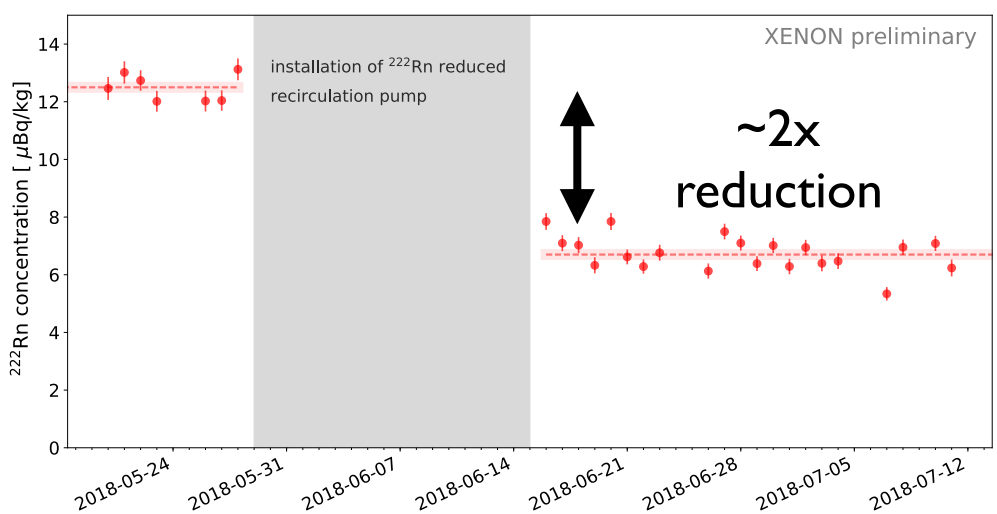




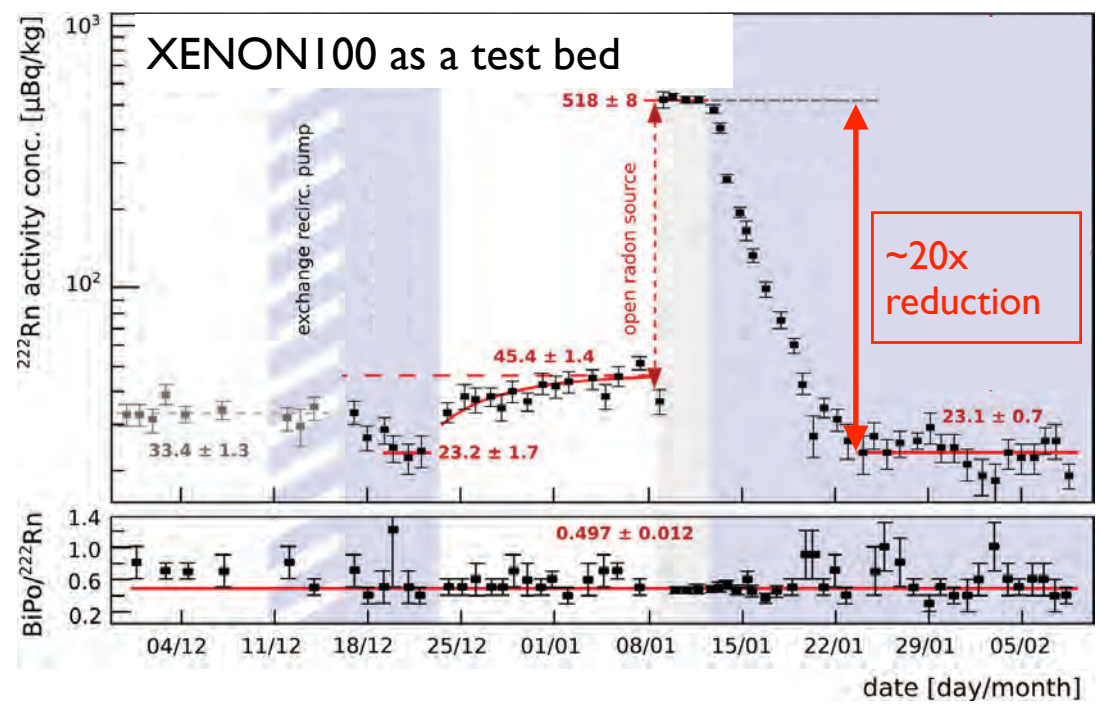
^{222}Rn Background

^{222}Rn contributions in XENON1T

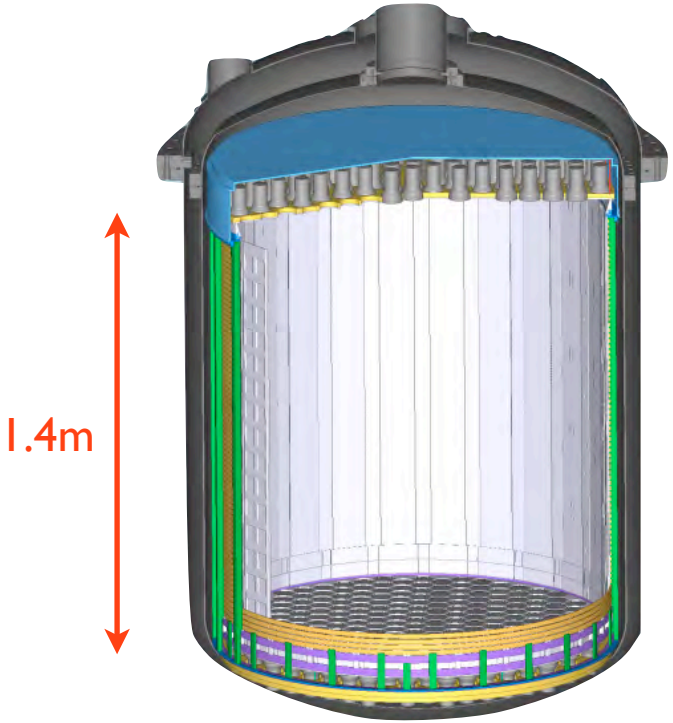


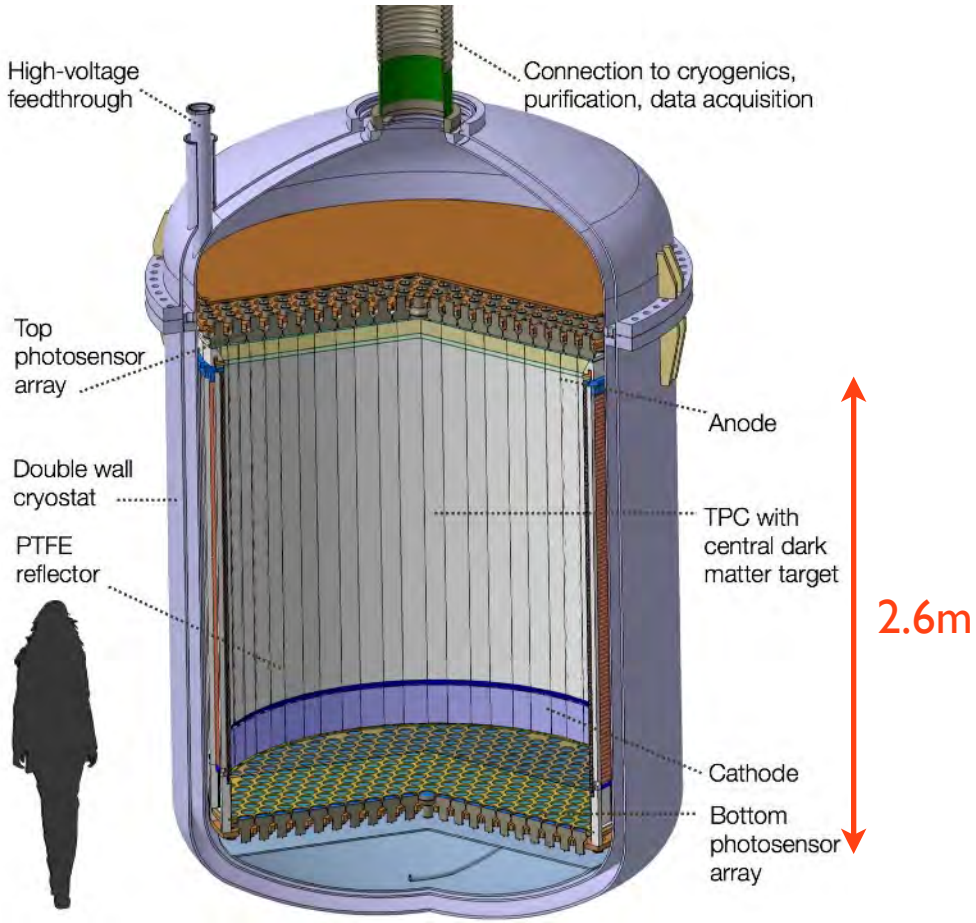


- Ten-fold radon reduction:
  - New pumps:
    - Novel magnetic piston pump R&D
  - Continuous radon distillation
    - Already shown to work



Even further downstream





XENONnT

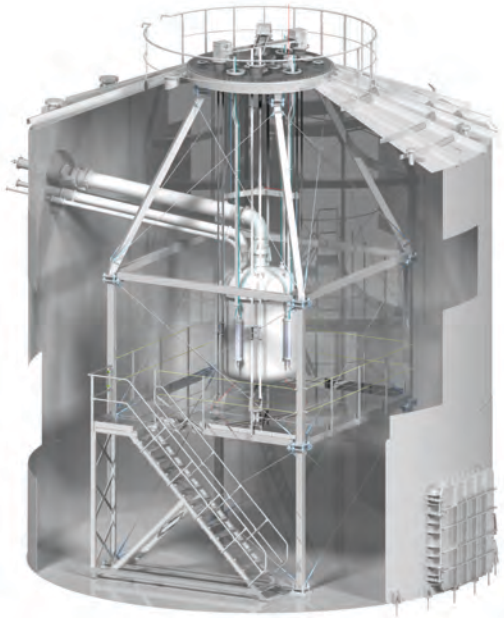
8t of LXe total
Reuse a lot of XENON1T infrastructure
Funding fully secured
Start in 2019

DARWIN

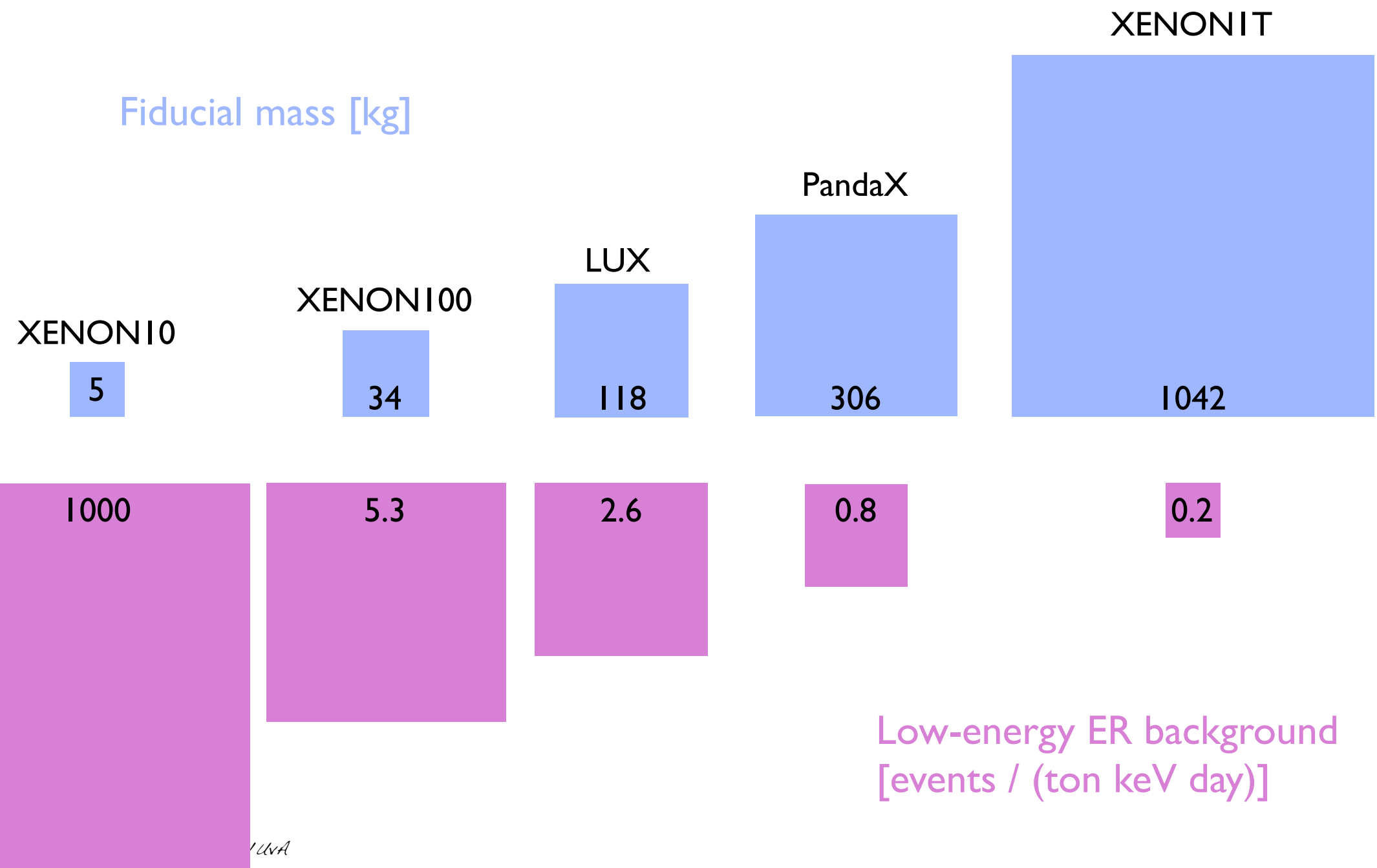
50t of LXe total
Global effort
Funded through 2 ERC grants
Start in 2025

Summary

- The XENON1T experiment is world's most sensitive direct detection dark matter experiment
- Achieved ~1 ton x year of exposure, unprecedented radiopurity
- Larger experiments will allow for more physics channels:
  - alternative DM particles, neutrino physics
- Planning XENONnT with 3x more Xe and 2x more PMTs
- Dreaming of 50t of Xe with DARWIN project…



LXe: Larger detectors, lower backgrounds



Cut & Count

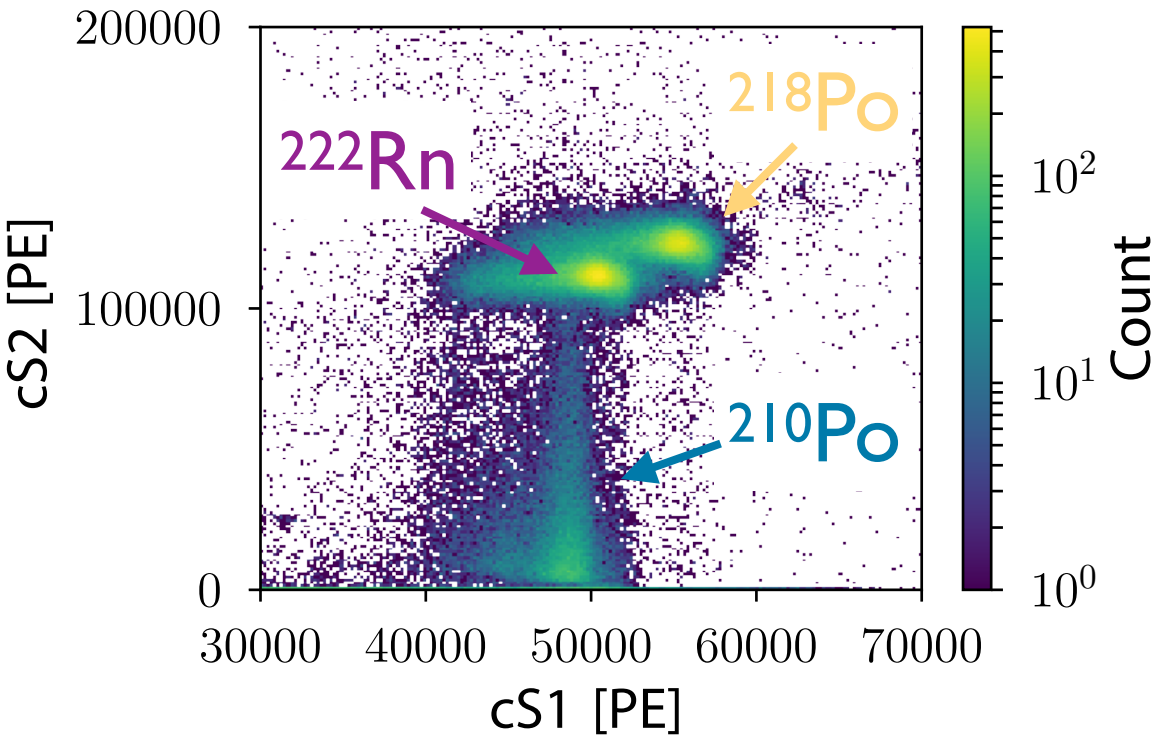
Mass	1.3 t	1.3 t	0.9 t	0.65 t
(cS1, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
$WIMP_{best\text{-}fit}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

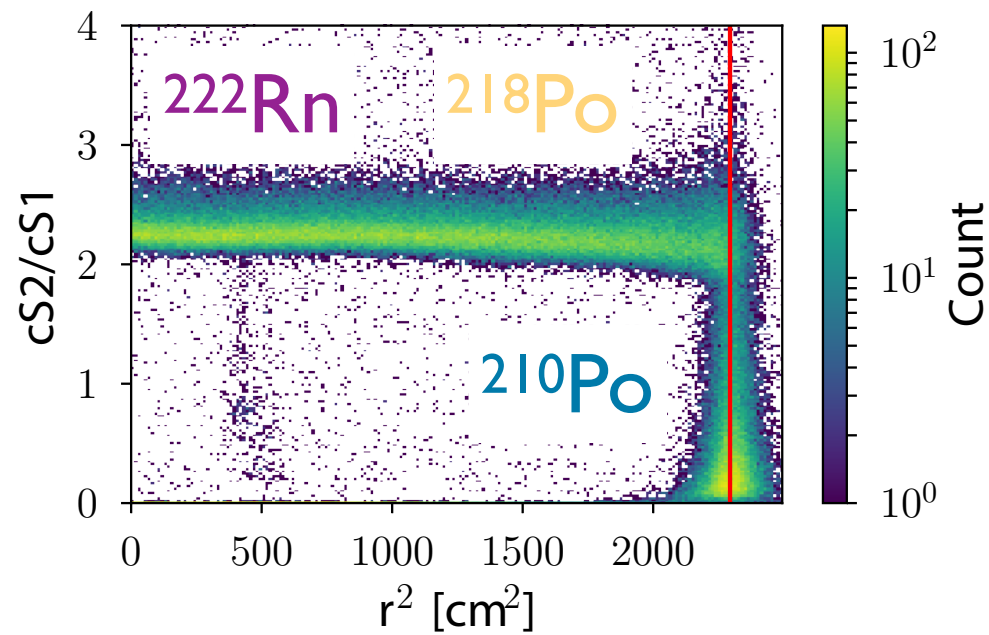
Using full S+BG model
(S1, S2, R, "Z") space

"Safe" reference regions

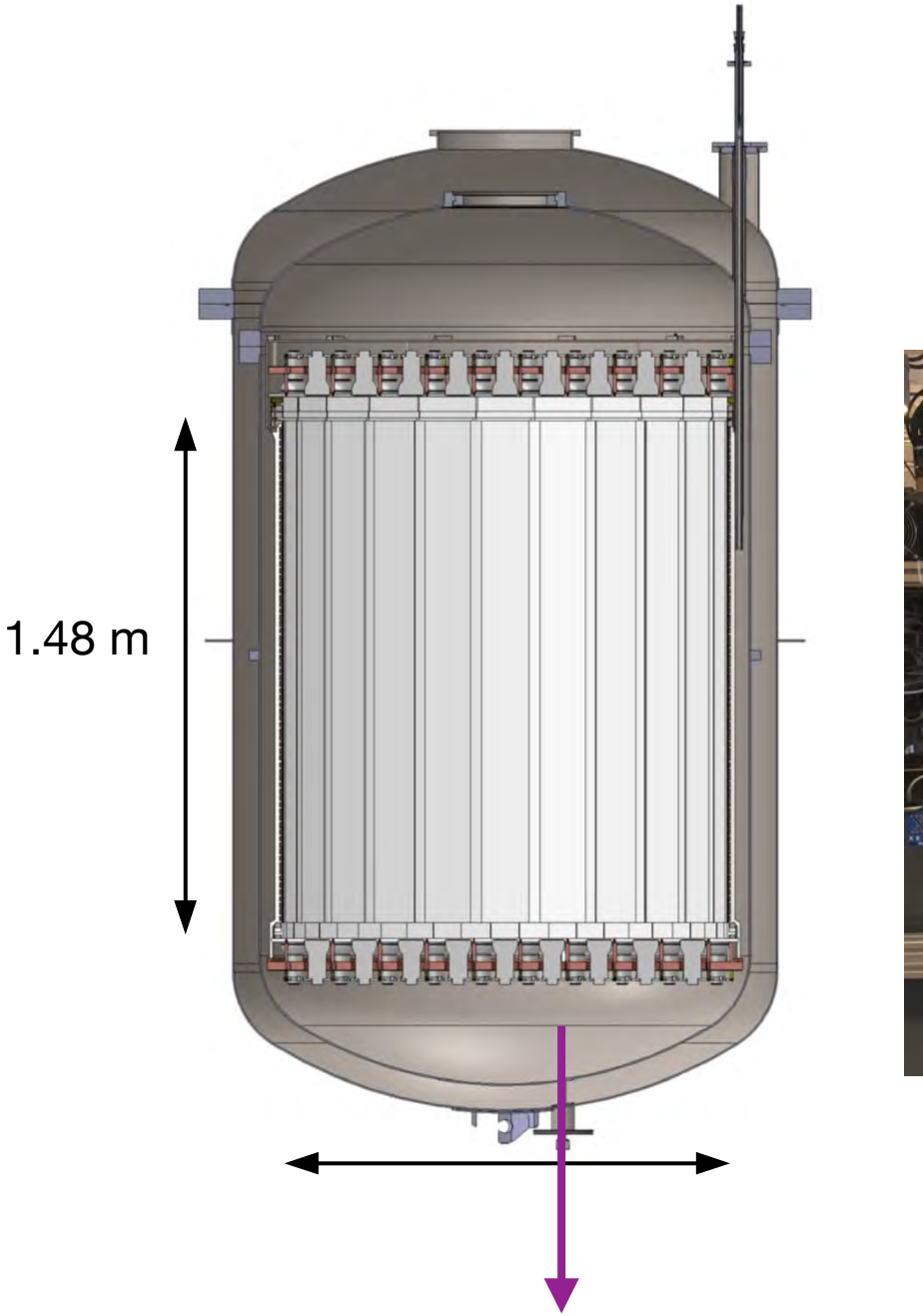
Plate out in PTFE

Thesis S.Breur





LXe purification



Demonstrator at Columbia